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DEPARTMENT OF TRANSPORTATION

COAST GUARD

Predictability of LNG Vapor Dispersion From Catastrophic Spills Onto Water:

AN ASSESSMENT

Prepared for

Cargo and Hazardous Materials Division
Office of Merchant Marine Safety
United States Coast Guard
Washington, D.C. 20590

April 1977

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Prepared by

10 Jerry A. Havens
Associate Professor of Chemical Engineering
University of Arkansas/
Technical Advisor
Cargo and Hazardous Materials Division

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The report "Predictability of LNG Vapor Dispersion from Catastrophic Spills onto Water: An Assessment" was prepared for the Coast Guard by Dr. J. A. Havens, Associate Professor of Chemical Engineering, University of Arkansas, while on sabbatical leave acting as Technical Advisor, Cargo and Hazardous Materials Division.

The report reviews the methods which have been used to predict the dispersion of flammable gases from a very large spill of liquefied natural gas (LNG) onto water. It provides a comprehensive description of these methods and contains an assessment of the present "state of the art" in predictability of vapor dispersion from such spills. The report recommends further work which should be done to increase confidence in such predictions.

This report should help to answer a number of questions which are frequently asked by persons interested in water transportation of this important cargo, and provides a recommended course of action which should provide answers to questions which remain regarding the dispersion of flammable vapors from large spills of hazardous materials. Comments and recommendations are solicited and should be sent to the Chief, Cargo and Hazardous Materials Division (G-MHM/83), U. S. Coast Guard, Washington, D.C. 20590.

W M Benkert
W. M. BENKERT
Rear Admiral, U. S. Coast Guard
Chief, Office of Merchant Marine Safety

Dist: (SDL No. 105)
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FOREWORD

This review of mathematical models which have been used to predict the downwind travel of flammable gas mixtures in the event of a catastrophic spill of liquefied natural gas onto water was undertaken while the author was on sabbatical leave from the Department of Chemical Engineering, University of Arkansas, serving as Technical Advisor, Cargo and Hazardous Materials Division, Office of Merchant Marine Safety, U.S. Coast Guard Headquarters, Washington, D.C.

The motivation for this review resulted from two needs of the Coast Guard:

1. The Coast Guard is actively developing, through contract research and in-house efforts, techniques for the assessment of hazards associated with the marine transportation of chemicals. A significant part of the hazardous nature of some chemicals shipped by water relates to fire and explosion behavior. The increasingly routine marine carriage of volatile flammable liquids and liquefied flammable gases in large quantities carries with it the risk of fire and explosion phenomena resulting from formation of large flammable vapor clouds in the event of an accident. The assessment of such risks and the development of emergency response procedures requires a methodology for predicting the extent and nature of flammable cloud formation in a variety of possible accident scenarios. Thus the Coast Guard has

a general need for accurate vapor dispersion models.

2. The proposed large scale importation of liquefied natural gas (LNG) into the United States is the subject of intense argument, particularly in relation to the assessment of risk to the public from accidental release of LNG as a result of ship collision. In the event of a catastrophic release it is considered highly likely that an immediate fire would ensue. However, in the event that ignition did not occur immediately, an LNG vapor cloud would form over and downwind of the spill site. Wide disagreement regarding the extent of travel (and the accompanying possible public exposure) of the flammable portion of such a cloud has contributed to an apparently growing concern regarding the risks associated with LNG importation. The Coast Guard is responsible for regulating the movement of LNG by water in the United States and thus has a specific interest in the development of accurate LNG vapor dispersion models. There appeared to be a need for a review and assessment of vapor dispersion predictability by someone not immediately involved in LNG safety related research.

Since the Coast Guard's primary interest is in LNG spills on water, this review was immediately restricted. Several models for LNG vapor dispersion which have been used primarily for analyzing vapor dispersion from land spills are essentially

identical to those reviewed herein. However, if they had not been used as a basis for published predictions of vapor dispersion from LNG spills on water they were not included. Furthermore, the scope of this review was limited to the predictability of dispersion from a very large LNG spill on water. No consideration was given to site-specific factors which may have an important bearing on the assessment of downwind flammable cloud travel, such as topographical features and structures. Likewise, no consideration was given to the specific applicability of weather conditions, since this would depend on the site involved as well as the traffic control measures which are imposed. For example, if LNG ship movement is restricted to daylight hours, the probability of a very large spill during stable or inversion conditions may be remote for some ports. My intent was to review published models used to predict downwind travel for a very large spill (25,000 M^3) and to identify and explain the differences in those models. I have also offered recommendations for future work based on the assessment of the models reviewed. There may also be other models proposed for the prediction of vapor dispersion from LNG spills on water which I have overlooked. If this is the case, such omission is due only to my time constraints for reviewing the literature.

This work could not have been completed without the excellent cooperation received from all of the parties whose work was reviewed. At my request, all of the groups clarified

questions which I had based on my review of the published models, and one group (Cabot Corporation) provided a computer program which I required to make predictions utilizing their model. However, if errors appear in the review they are my own product.

The reader should be aware that the presentation of these models gives no insight into the historical perspective in which they might be viewed. A close look at the literature cited in this report indicates that there was indeed a "development" process involved in the formulation of these models for LNG vapor dispersion. It is not surprising that the models which are recommended for further use and evaluation are in a real sense the product of efforts to modify or build on the efforts of the earlier investigators in the field.

In order to insure accuracy of description and interpretation of the models reviewed herein, a draft of this report was sent to all parties whose work is discussed with a request that they examine the description of their model for technical and interpretive accuracy. Comments were received from all of the groups and were carefully considered in the preparation of the final report. Corrections and revisions of the draft report were made in several instances as a result of the comments received. For the sake of completeness, the comments on the draft report are appended.

J. A. HAVENS

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III. EXECUTIVE SUMMARY

A number of predictions of LNG vapor cloud formation and dispersion which might result from a catastrophic LNG spill onto water have been published. The predictions of the following groups have been repeatedly cited in the literature related to safety of marine LNG transportation:

1. U.S. Bureau of Mines - Burgess et al. (1, 2)
2. American Petroleum Institute - Feldbauer et al. (3)
3. Cabot Corporation - Germeles and Drake (4)
4. U.S. Coast Guard CHRIS (Chemical Hazard Response Information System) - Arthur D. Little, Inc. (5)
5. Professor James Fay, Massachusetts Institute of Technology (6)
6. Federal Power Commission (7)
7. Science Applications, Inc. (8)

Order of magnitude differences in the predictions, based on these models, of the extent of flammable vapor/air mixtures following a catastrophic spill are significant in the overall assessment of the potential risk of marine transportation of LNG.

The purpose of this study is fivefold:

1) To provide a detailed description of the mathematical models upon which published predictions of LNG vapor travel downwind of catastrophic LNG spills onto water have been based.

2) To estimate, using these models, the maximum downwind travel of flammable LNG vapor/air mixtures for a "standard" spill scenario, so that a valid comparison can be made of the results obtained when the different models are used to describe the same event;

3. To identify the reason for differences in predictions which occur when the models are used to describe the same event, and to assess the technical credibility of the methodology which results in such differences.

4. To define the present "state of the art" in predictability of LNG vapor dispersion from catastrophic spills onto water, with emphasis on the extent to which the present state of the art justifies reliance on existing published predictions in formulating LNG safety management programs.

5. To provide recommendations for further work which would increase confidence in the predictability of vapor dispersion from catastrophic LNG spills onto water.

The models used by the groups cited above for prediction of vapor cloud formation and dispersion can be categorized as follows:

1. Predictions which utilize classical air pollutant dispersion models which were developed to describe relatively near-field dispersion of neutrally buoyant materials. These models are based on the general observation that the concentration profiles downwind of a pollutant source can

be represented by a Gaussian or Normal distribution. This model type is subdivided to describe two different dispersion phenomena.

a. Dispersion of an essentially instantaneous release of a pollutant into the atmosphere, the dispersion being associated with the growth of this instantaneously released "puff", or cloud, as it is being translated by the wind. The predictions due to Fay, Germeles and Drake, and CHRIS utilize this type of model.

b. Dispersion of material which is being emitted at a continuous steady rate forming a "plume" downwind of the emission source. The predictions of Burgess, Feldbauer, and the FPC utilize this type of model.

2. Predictions based on solution of the combined mass, momentum and energy balance equations. (The classical air pollutant dispersion equations of category 1 above are a special case where energy effects and momentum effects are not considered). The SAI predictions utilize this type of model.

The "standard scenario" LNG spill which is assumed in this report for purposes of comparison of the above models is an instantaneous release of 25,000 cubic meters of LNG onto water. It is considered that such an event provides a conservative upper limit on the severity of a spill which might conceivably occur.

Table III-1 shows the maximum downwind distance to the time-average 5% vapor concentration level following an instantaneous 25,000 cubic meter spill as predicted by the models suggested by the seven groups above. The distances, with the exception of the estimate attributed to SAI, were computed by the author using the procedure suggested by the investigating groups cited. The corresponding distance for SAI's model could not be computed due to the proprietary nature of the SAI computer model. Table III-1 therefore includes, for comparison, the distance predicted by SAI for a 37,000 cubic meter spill as described in their risk assessment study prepared for the Western LNG Terminal Company (8). In reviewing Table III-1, it should be noted that the meteorological conditions suggested as applicable by the groups are not necessarily the worst that might have been assumed. Specifically,

1. The 0.75 mile distance obtained with the FPC model reflects the assumption of neutral atmospheric stability values (Pasquill D), as recommended by the FPC staff.

2. The 5.2 mile distance obtained with the American Petroleum Institute Model assumes vertical dispersion characterized as Singer and Smith D and horizontal dispersion characterized as Pasquill C, following the procedure suggested by Feldbauer (2).

3. The SAI prediction assumes neutral atmospheric stability; however the result is claimed to be essentially

TABLE III-1

MAXIMUM DOWNWIND DISTANCE TO TIME-AVERAGE 5%
CONCENTRATION LEVEL FOLLOWING 25,000 M^3
INSTANTANEOUS SPILL OF LNG ONTO WATER

(Assumes 5 MPH Wind except as noted and Meteorological Conditions Considered Applicable by Investigating Groups)

Model	Distance (MILES)
U. S. Bureau of Mines (1,2)	25.2 - 50.3*
American Petroleum Institute (3)	5.2
Cabot Corporation (4)	11.5
U. S. Coast Guard CHRIS (5)	16.3**
Professor James Fay (6)	17.4**
Federal Power Commission (7)	0.75
Science Applications, Inc. (8)	1.2***

* A range was presented to indicate uncertainty in vapor evolution rate

** Wind velocity not considered explicitly in model

*** For 37,500 cubic meter instantaneous release, wind velocity = 6.7 MPH

the same when stable atmospheric conditions are assumed. The SAI model also gives longer downwind travel distances when <u>higher</u> wind velocities are assumed, in contrast to the other models.

4. The predictions obtained using the Bureau of Mines (Burgess) model, the CHRIS model, Fay's model, and the Cabot (Germeles and Drake) model assume stable atmospheric conditions.

The variation in the predictions shown in Table III-1 is significant in assessing the potential hazard associated with a large accidental release of LNG on water if the release should occur without immediate ignition of the flammable vapor mixture at the spill site. The probability of the cloud reaching the maximum distance at which a 5% concentration just persists is, however, considered very low due to the anticipated contact with ignition sources which would develop as a result of frictional heating accompanying such catastrophic accidents. Even if the cloud were not ignited at the spill site it is unlikely that the cloud would travel over populated areas, to the extent predicted by the models in Table III-1, without being ignited. Nevertheless, the predictability of vapor dispersion from a

catastrophic release of LNG onto water does have a bearing on the routing and traffic control of vessels as well as for emergency response considerations. Furthermore, a reasonably accurate prediction of the dispersion process is required for a characterization of cloud burning and to assess potential damage which might result from explosions of vapor/air mixtures, if such explosions are possible. Although the experience to date indicates that detonation of unconfined LNG vapor/air mixtures is not likely, a good method of vapor dispersion prediction would be valuable in attempts to understand the circumstances under which detonations of vapor/air mixtures might be expected, such as partial confinement and high energy initiation.*

Analysis of the models and the results predicted for dispersion from a 25,000 cubic meter instantaneous spill indicate that all of the variation in results shown in Table III-1 for the classical air pollutant dispersion models can be attributed to four factors.

1. The methods used to estimate the rate at which the vapor enters the atmosphere from the liquid LNG pool results in estimates thereof ranging from 1.43 x 10^5 ft^3/sec (FPC) to 2.0 x 10^6 ft^3/sec (at atmospheric

* The Coast Guard is presently sponsoring a test program at the Naval Weapons Center, China Lake, CA., to determine the burning characteristics of large vapor clouds (39).

pressure, $70^{o}F$) (Burgess). This factor is primarily responsible for the very short distance predicted by the FPC.

2. Four of the classical models incorporate effects associated with the gravity induced spreading of the cold LNG vapors (FPC, Feldbauer, Fay, Germeles, and Drake); two do not (Burgess, CHRIS). Those models which do incorporate such effects assume a sequential process; spill-pure vapor cloud formation - gravity spread with or without air entrainment - dispersion by atmospheric turbulence. The specific method of treatment differs widely, and the resulting differences are reflected in the varied predictions of downwind distance shown in Table III-1.

3. Some of the models (Feldbauer, CHRIS, FPC, Germeles and Drake) incorporate corrections for the area nature of the source (the classical equations used in all of the models are derived for a point source emission), while others do not (Burgess, Fay). The method of treatment of the area nature of the source appears relatively unimportant to the final differences in results, except for Feldbauer's model, whose result is strongly influenced.

4. The predictions do not all assume the same atmospheric stability categories. Atmospheric stability

considered applicable for such a prediction varies from neutral to very stable, with a strong effect on the results.

The following conclusions are drawn:

1. This review and comparison of published predictions of the downwind travel of flammable gas-air mixtures following the instantaneous release of 25,000 cubic meters of LNG onto water identifies the sensitivity of such predictions to the following factors.

   a. Characterization of atmospheric turbulence (stability)

   b. Allowances for area-source effects

   c. Specification of vapor release rate

   d. Allowances for gravity spread/air entrainment effects

2. The shortest distance to the time average 5% concentration level for a 25,000 cubic meter instantaneous spill predicted by the models reviewed herein is 0.75 miles. This distance, predicted by the FPC model, results primarily from the use of an unrealistically low vapor release rate and the use of neutral atmosphere stability characteristics. The FPC estimate, in the author's opinion, is not justified.

3. At the other extreme, distances of the order of tens of miles are predicted for a 25,000 cubic meter instantaneous spill under stable weather conditions using continuous plume models (Burgess) which do not account for any heat transfer or momentum transfer effects. Such estimates are not justified in this author's opinion.

4. Intermediate distances to the 5% concentration level are predicted for a 25,000 cubic meter spill during stable weather conditions by Germeles and Drake (11.5 miles), Fay (17.4 miles) and the CHRIS model (16.3 miles). The difference in predicted downwind distances obtained with the CHRIS and Germeles-Drake models can be attributed primarily to the inclusion of gravity spread/air entrainment effects in the Germeles and Drake Model. The rough agreement of these two predictions with the value of 17.4 miles predicted by Fay must be considered fortuitous since the modeling process assumed by Fay is quite different from the other two. Professor Fay now believes (42) that his model should be used with different assumptions than originally described by Lewis and Fay, in which case substantially longer distances result. In the author's opinion, the model of Germeles and Drake provides a more plausible estimate of the LNG dispersion process following a large rapid spill than the Fay or CHRIS models, since the model incorporates a rational, if simplified, description of an anticipated gravity spread phase. Further effort to

improve this type model as an alternative to a more complex numerical procedure has merit, particularly for routine usage where time and expense constraints are important.

5. The estimate, using Feldbauer's model, of 5.2 miles for the downwind distance to the 5% concentration level following a 25,000 cubic meter spill can be attributed to the predicted dilution and corresponding extreme width (~2 miles) of the cloud at the end of the gravity spread phase. Feldbauer's allowance for air entrainment during the gravity spread, which involves the assumption of a constant cloud depth, is based on observations of small spills (10 M^3) and the extension to very large spills appears uncertain. Further, representation of the cloud at the end of the gravity spread phase as a series of dispersed point sources on a line perpendicular to the direction of cloud travel is not realistic in view of the resulting prediction of shorter distances with increasing atmospheric stability.

6. The primary reason for the even shorter downwind distance (~1 mile) to the 5% concentration level predicted by SAI for an even larger (37,500 cubic meters) spill appears to be the predicted highly turbulent motion and associated air entrainment induced during the gravity spread phase of the cloud.

7. In the author's opinion, the predicted maximum distances of about 5 miles by Feldbauer and about 1 mile by SAI for

flammable cloud travel following instantaneous release of 25,000 cubic meters of LNG onto water cannot be rationalized on the basis of any argument thus far advanced except that of gravity spread/air entrainment effects, and experimental verification of these effects has not been adequately demonstrated.

8. It was not possible within the limits imposed by this review to evaluate the accuracy of the predictions published by SAI. Rather, the author has reviewed the methodology described by SAI and believes that such techniques hold the most promise for accurate prediction of vapor dispersion from catastrophic spills on water. A program designed to evaluate the accuracy of the SAI model or other models of similar generality should now be considered high priority. The Recommendations section of this report addresses this need.

The following recommendations are made:

1. The Science Applications, Inc. (SAI) LNG vapor dispersion model should be more thoroughly evaluated. This will require the cooperation of SAI due to the proprietary nature of their computer programs which are required for solution of the model equations. Further evaluation of the SAI model, or other similar models based on simultaneous solution of the mass, momentum and energy balance equations which may become available, should address the following requirements:

a. The methodology of describing turbulent mass, momentum and energy transfer should be critically evaluated. A literature search should be conducted to identify and evaluate experimental data supporting the assumption of first-order (eddy diffusivity, thermal conductivity and viscosity) turbulent transfer phenomenological relationships for describing turbulent transfer in the lower atmosphere.

b. An error analysis should be done to provide some means for estimating the confidence level in the technique used to assign numerical values to the turbulent transfer coefficients.

c. Sufficient calculations should be made with the model to determine the sensitivity of the results predicted by the model to uncertainties in the transfer coefficients identified in b. above.

d. An analysis should also be made of the liquid spread, vapor generation, and heat transfer models used in the specification of the boundary conditions to determine the sensitivity of the model predictions.

e. The numerical stability and accuracy of the algorithm used for computer solution of the equations should be critically evaluated.

2. A series of computations should be made, using the SAI model, of the downwind distance to the time average 5% concentration level for "instantaneous" LNG spills as

a function of spill size. The range of spill sizes should be from 10 cubic meters to 25,000 cubic meters with sufficient points between to adequately characterize the predicted relationship between flammable cloud travel and spill size.

3. The result of 2 above should be compared with a similarly prepared relationship between flammable cloud travel and spill size predicted using the Germeles and Drake model described in this report. It is anticipated that the results will be in substantial agreement for very small spill sizes but the comparison should indicate the smallest spill sizes for which significant differences appear in predicted downwind distance. Such a comparison should also provide guidance for determining a lower bound on the size of experimental spills which may be required to assess large spill behavior.

4. In anticipation of experimental spills which may be required to provide confidence in predictions of large spill behavior, an evaluation should be made of the experimental data requirements associated with verification of model predictions.

5. Additional experimental spills should be performed only after completion of the program outlined above, and such spills should be performed for the purpose of model evaluation. Large "demonstration spills" have been

suggested recently, largely as a result of the variation in predictions which has been the subject of this report. It is the opinion of this author that validation of models should still be the primary goal of further test programs; "demonstration" of the effects of large spills without heavy reliance on models should be avoided.

IV. INTRODUCTION

A number of predictions of LNG vapor cloud formation and dispersion which might result from a catastrophic LNG spill onto water have been published. Order of magnitude differences in these predictions of the area adjacent to the spill which could be exposed to flammable LNG vapor/air mixtures are significant in the overall assessment of the potential risk of marine transportation of LNG.

With respect to LNG spills onto water, the predictions of the following groups have been repeatedly cited in the literature related to safety of marine LNG transportation:

1. U. S. Bureau of Mines - Burgess et al. (1, 2)
2. American Petroleum Institute - Feldbauer et al. (3)
3. Cabot Corporation - Germeles and Drake (4)
4. U. S. Coast Guard CHRIS (Chemical Hazard Response Information System) - Arthur D. Little, Inc. (5)
5. Professor James Fay, Massachusetts Institute of Technology (6)
6. Federal Power Commission (7)
7. Science Applications, Inc. (8)

Other groups have published information related to vapor dispersion from LNG spills onto water (9, 10, 11). However, these studies have not resulted in predictions of downwind travel of flammable gas mixtures to be expected in large accident scenarios and were therefore not reviewed in this report.

In addition, numerous studies have been made concerning the dispersion of vapor clouds from LNG spills on land. For an extensive citation of such work, the reader is referred to U. S. Coast Guard document CG-478, "Liquefied Natural Gas - Views and Practices - Policy and Safety", 1 February 1976, available from the Cargo and Hazardous Materials Division (G-MHM/83), U. S. Coast Guard, Washington, D.C., 20590.

Table IV-1 shows the maximum downwind distance to the time-average 5% vapor concentration level following an instantaneous 25,000 cubic meter spill as predicted by the models suggested by the seven groups above. The distances, with the exception of the estimate attributed to SAI, were computed by the author using the procedure suggested by the investigating groups cited. The corresponding distance for SAI's model could not be computed due to the proprietary nature of the SAI computer model. Table IV-1 therefore includes, for comparison, the distance predicted by SAI for a 37,000 cubic meter spill as described in their risk assessment study prepared for the Western LNG Terminal Company (8). In reviewing Table IV-1, it should be noted that the meteorological conditions suggested as applicable by the groups are not necessarily the worst that might have been assumed. Specifically,

1. The 0.75 mile distance obtained with the FPC model reflects the assumption of neutral atmospheric stability values (Pasquill D), as recommended by the FPC staff.

TABLE IV-1

MAXIMUM DOWNWIND DISTANCE TO TIME-AVERAGE 5% CONCENTRATION LEVEL FOLLOWING 25,000 M^3 INSTANTANEOUS SPILL OF LNG ONTO WATER (Assumes 5 MPH Wind except as noted and Meteorological Conditions Considered Applicable by Investigating Groups)

MODEL	DISTANCE (MILES)
U. S. Bureau of Mines (1, 2)	25.2 - 50.3*
American Petroleum Institute (3)	5.2
Cabot Corporation (4)	11.5
U. S. Coast Guard CHRIS (5)	16.3**
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Science Applications, Inc. (8)	1.2***

* A range was presented to indicate uncertainty in vapor evolution rate

** Wind velocity not considered explicitly in model

*** For 37,500 cubic meter instantaneous release, wind velocity = 6.7 MPH

2. The 5.2 mile distance obtained with the American Petroleum Institute Model assumes vertical dispersion characterized as Singer and Smith D and horizontal dispersion characterized as Pasquill C, following the procedure suggested by Feldbauer (3).

3. The SAI prediction assumes neutral atmospheric stability; however the result is claimed to be essentially the same when stable atmospheric conditions are assumed. The SAI model also gives longer downwind travel distances when higher wind velocities are assumed in contrast to the other models.

4. The predictions obtained using the Bureau of Mines (Burgess) model, the CHRIS model, Fay's model, and the Cabot (Germeles and Drake) model assume stable atmospheric conditions.

The results shown in Table IV-1 are specifically for a 25,000 cubic meter instantaneous spill (except as noted for Sciences Applications, Inc.). These predictions do not consider the possibility that flammable concentrations of vapor might exist at greater distances, since the 5% level used for the calculation must be considered a time-average concentration. Nevertheless, the variation shown reasonably characterizes the extreme range of predicted results which is the basis for the present controversy regarding the assessment of the vapor cloud hazard from LNG spills.

The variation in these predictions is significant in assessing the potential hazard associated with a large accidental release of LNG on water if the release should occur without immediate ignition of the flammable vapor mixture at the accident site. The sudden release of large amounts of LNG onto water is practically realizable only as a result of a high energy collision. Immediate ignition is considered extremely likely if such a collision should occur, because of the frictional heating anticipated with such a collision and ignition sources which would result from damaged equipment. If ignition of the vapors does not occur at the spill site, formation of a large vapor cloud also presupposes the virtual absence of ignition sources in the area close to where the cloud is being formed. For these reasons, an accident scenario which assumes formation of a vapor cloud extending over large populated areas before ignition is extremely unlikely, even if formation of such clouds might occur in the absence of ignition.

However, the predictability of dispersion of vapors from accidental, catastrophic release of LNG does have a bearing on the safety related management of LNG vessel traffic, as it does on the management of other hazardous cargoes. This is true because the zone around an accident which might be subjected to flammable vapor concentrations resulting fron non-ignited spills (however remote the probability) has an effect on the routing and traffic control of vessels and would influence emergency response procedures. Furthermore, although it appears

extremely unlikely that large populated areas could be exposed to a flammable vapor cloud, since ignition is likely when the advancing front of the cloud reaches such areas, the ability to predict dispersion is required to assess the damage which would result from an early ignition. This is true for two reasons. First, the burning of a flammable cloud cannot be adequately predicted without knowledge of the composition of the cloud. Second, an ability to predict vapor dispersion is required to assess potential damage which might result from detonations of vapor-air mixtures. Although the experience to date indicates that detonation of unconfined LNG vapor-air mixtures is not likely, a good method of vapor dispersion prediction would be valuable in attempts to understand the circumstances under which LNG vapor-air (or a variety of other fuels and chemicals) detonations might be expected, such as partial confinement and high energy initiation.

The purpose of this study is fivefold:

1. To provide a detailed description of the mathematical models upon which published predictions of LNG vapor travel downwind of catastrophic LNG spills onto water have been based.

2. To estimate, using these models, the maximum downwind travel of flammable LNG vapor-air mixtures for a "standard" spill scenario, so that a valid comparison can be made of the results obtained when the different models are used to describe the same event.

3. To identify the reason for differences in predictions which occur when the different models are used to describe the same event, and to assess the technical credibility of the methodology which results in such differences.

4. To define the present "state of the art" in LNG vapor dispersion modeling, with particular emphasis on the extent to which the present state of the art justifies reliance on existing published predictions in formulating LNG safety management programs.

5. To provide recommendations for further work which would increase confidence in the predictability of vapor dispersion from LNG (and other volatile chemicals) accidentally spilled on water.

The "standard scenario" LNG spill which is assumed in this report for purposes of comparison of the above models is an instantaneous release of 25,000 cubic meters of LNG onto water. 25,000 cubic meters is representative of the largest single-tank capacity of ships constructed to date or on order. Although as many as six tanks may be incorporated into an LNG ship, an accident resulting in simultaneous rupture of more than two tanks is not considered credible. In the event of simultaneous rupture of two tanks, instantaneous release from both tanks is not considered credible. The vapor travel following instantaneous release of 25,000 cubic meters would be expected to be even more extensive than would be expected from the actual release of LNG following simultaneous rupture of two 25,000 cubic meter tanks. Thus, the instantaneous release of 25,000 cubic meters of LNG

on water provides a conservative upper limit on the size of a spill which might conceivably occur, even though such a spill is considered extremely unlikely.

V. BASIS FOR LNG VAPOR DISPERSION MODELS

A number of different predictions of LNG vapor cloud formation and dispersion resulting from an accidental LNG spill onto water have been published. Although the predictions reflect wide disagreement by the parties involved as to the extent of hazard associated with downwind travel of flammable gas-air mixtures, it is important to realize that all of the mathematical models that have been used to make such predictions have a common basis. It is therefore expedient to provide the necessary physical and mathematical basis which is common to all models to be discussed.

V-A. PHYSICAL PROCESSES INVOLVED IN LNG VAPOR DISPERSION

LNG vapor dispersion in the atmosphere involves the mixing with air of a gas which is much colder and denser than air. A valid description of the process should account for the following processes, which may occur simultaneously:

1. Heat transfer effects due to mixing the cold gas, formed from the boiling LNG, with warmer air (which may contain water vapor), and heat transfer from beneath the cloud (ground or water).

2. Gravity-induced spreading effects resulting from non-uniform density.

3. Dispersion (dilution with air) of the gas due to turbulent fluid motion.

The heat transfer and gravity spreading effects can be described in mathematical equation form by application of the principles of accountability of energy and accountability of momentum. The concentration variations in the LNG vapor/air mixture can be described in mathematical equation form by application of the principle of accountability of mass. The general equations of accountability of energy, momentum, and mass are, respectively:

Accountability of Energy

$$\underbrace{\frac{\partial \rho H}{\partial t}}_{\mathrm{I}} = \underbrace{-\nabla\cdot\rho H\vec{v} - \nabla\cdot\vec{q} + \frac{DP}{Dt}}_{\mathrm{II}} - \underbrace{\vec{\vec{\tau}}:\nabla\vec{v}}_{\mathrm{III}} \qquad \text{(V-1)}$$

Accountability of Momentum*

$$\underbrace{\frac{\partial \rho\vec{v}}{\partial t}}_{\mathrm{I}} = \underbrace{-\nabla\cdot\rho\vec{v}\vec{v} - \nabla\cdot\vec{\vec{\tau}}}_{\mathrm{II}} + \underbrace{\rho\vec{g}}_{\mathrm{III}} \qquad \text{(V-2)}$$

Accountability of Mass**

$$\frac{\partial \rho}{\partial t} = -\nabla\cdot\rho\vec{v} \qquad \text{(total mass)} \qquad \text{(V-3a)}$$

$$\underbrace{\frac{\partial C}{\partial t}}_{\mathrm{I}} = \underbrace{-\nabla\cdot C\vec{v}}_{\mathrm{II}} \qquad \text{(methane or LNG component)} \qquad \text{(V-3b)}$$

where ρ = density of air-gas mixture

H = enthalpy (energy content) of air-gas mixture

$\vec{v}$ = velocity vector, decomposible into x, y, z components u, v, w, respectively

$\vec{q}$ = heat transfer vector, decomposible into components q_x, q_y, q_z

P = pressure

t = time

* Coriolis Forces have been neglected

** Molecular Diffusion has been neglected

$\vec{g}$ = gravity force vector, decomposible into 3 components $g_x=0$, $g_y=0$, g_z

C = concentration of gas-air mixture

$\overleftrightarrow{\tau}$ = stress tensor, decomposible into 9 components τ_{xx}, τ_{xy}, τ_{xz}, τ_{yx}, τ_{yy}, τ_{yz}, τ_{zx}, τ_{zy}, τ_{zz}

Each of the above equations can be understood as being a statement of the general principle of accountability:

"The rate of accumulation of a quantity (energy, momentum, or mass) at a given location is equal to the net rate at which the quantity is transferred into (or out of) that location from its surroundings, plus the rate at which that quantity is being produced at that location."

The groups of terms labelled I, II, III respectively in Equations V-1, 2, 3 correspond to the accumulation, transfer, and production mentioned above and are further explained in Table V-1.

Equations V-1, 2, 3 are differential equations. Use of these equations to describe LNG vapor dispersion requires specification of initial conditions and boundary conditions. Initial conditions include a description of the water and atmospheric conditions at the site and a description of the initiation of the spill. Boundary conditions may also include water and atmospheric conditions but in addition include description of momentum, energy, and mass transfers at the boundary of the region being modeled. In

TABLE V-1

IDENTIFICATION OF TERMS IN ENERGY, MOMENTUM, AND MASS BALANCE EQUATIONS (V-1, 2 3)

QUANTITY	ACCUMULATION TERMS (I)	TRANSFER TERMS (II)	PRODUCTION TERMS (III)
Energy	$\frac{\partial H}{\partial t}$ (Rate of change of energy with respect to time)	$\nabla \cdot \rho H \vec{v}$ (Energy carried along with fluid flow) $\nabla \cdot \vec{q}$ (Heat transfer due to temperature gradients) $\frac{DP}{Dt}$ (Work energy transfer due to pressure gradients)	$\overleftrightarrow{\tau} : \nabla \vec{v}$ (Thermal energy production due to fluid friction)
Momentum	$\frac{\partial \rho \vec{v}}{\partial t}$ (Rate of change of momentum with respect to time)	$\nabla \cdot \rho \vec{v} \vec{v}$ (Momentum carried along with fluid flow) $\nabla \cdot \overleftrightarrow{\tau}$ (Momentum transferred due to fluid friction or velocity gradients)	$\rho \vec{g}$ (Momentum production due to gravity forces)
Mass	$\frac{\partial \rho}{\partial t}$ (Rate of change of density with respect to time) $\frac{\partial C}{\partial t}$ (Rate of change of concentration with respect to rime)	$\nabla \cdot \rho \vec{v}$ (Mass transfer by fluid flow) $\nabla \cdot C \vec{v}$ (LNG Vapor transfer by fluid flow)	0 0

theory, the differential equations, along with prescribed initial and boundary conditions can be solved to obtain a complete description of the cloud behavior. However, a considerable quantity of additional information must be available as input to the solution of these equations, and solution for the general three-dimensional case is not practically realizable.

V-B. SIMPLIFICATION OF GENERAL MODEL FOR PRACTICAL APPLICATION

In practice, simplifying assumptions are made in the general mathematical models in order to arrive at a model for which a relatively few input data are required and which do not require excessive solution time and expense. It is in the simplification of the general model for the purpose of predicting LNG vapor dispersion that the differences between various investigators' predictions result.

Classical prediction of pollutant dispersion in the atmosphere, which in theory should be described with Equations V-1,2, 3, has focused primarily on dispersion of relatively small quantities of material such as smoke, radioactive isotopes, chemical fumes and dusts. In such situations it is commonly assumed that the pollutant material is present in sufficiently small quantities that it does not directly affect the motion of the air into which it is placed. Rather, the notion is that the pollutant particles simply follow the (already established) motion of the air. In such cases, material being dispersed can be

viewed as "tracers" of the air motion. Implicit in this approach is the assumption that there are no heat transfer effects between the pollutant and the air and that there is no momentum exchange between the two. In such a case, the requirement for the energy and momentum balances is eliminated. With the additional assumption that the material has the same density as air (i.e. the mixture is "neutrally buoyant"), the system of Equations V-1, 2, 3 reduces to one equation for the conservation of LNG vapor:

$$\frac{\partial C}{\partial t} = -\nabla \cdot C\vec{v} \qquad \text{(V-4)}$$

The quantity $C\vec{v}$, where C is the concentration of the pollutant in mass per unit volume and $\vec{v}$ is the local velocity, has the physical units of a mass flux term, i.e. mass/ area - time. The quantity $C\vec{v}$ must be related to the concentration profile in order to get an equation which can be solved. To this end it is commonly assumed that the mass flux is proportional to the concentration gradient. In this case,

$$C\vec{v} = -k\nabla C \qquad \text{(V-5)}$$

where ∇C = the local concentration gradient

k = the "Ficks Law" diffusion coefficient

Substituting Equation V - 5 into Equation V - 4 we have

$$\frac{\partial C}{\partial t} = \nabla \cdot k \nabla C \qquad \text{(V-6)}$$

V-B-I. Instantaneous Release (Puff) Model

If the pollutant is assumed to enter the atmosphere instantaneously, in amount Q, from a single point, the solution to Eq (V - 6) is

$$C(x,y,z,t) = \frac{Q}{(4\pi t)^{3/2}(K_x K_y K_z)^{1/2}} \exp\left[-\frac{1}{4t}\left[\frac{x^2}{K_x} + \frac{y^2}{K_y} + \frac{z^2}{K_z}\right]\right] \quad \text{(V-7)}$$

where K_x, K_y, K_z are constant diffusion coefficients for diffusion in the x, y, z directions, respectively

Furthermore, arguments based on statistical analyses of random turbulence (13) indicate that for large diffusion times (how large is large enough depends on the particular application, and in any case is not readily determined), the mean square diffusion distance is given by

$$\begin{aligned} \overline{x^2(t)} &= \sigma_x^2 = 2K_x t \\ \overline{y^2(t)} &= \sigma_y^2 = 2K_y t \\ \overline{z^2(t)} &= \sigma_z^2 = 2K_z t \end{aligned} \quad \text{(V-8)}$$

where σ_x, σ_y, σ_z are the standard deviations of the concentration distributions in the yz, xz, and xy planes, respectively

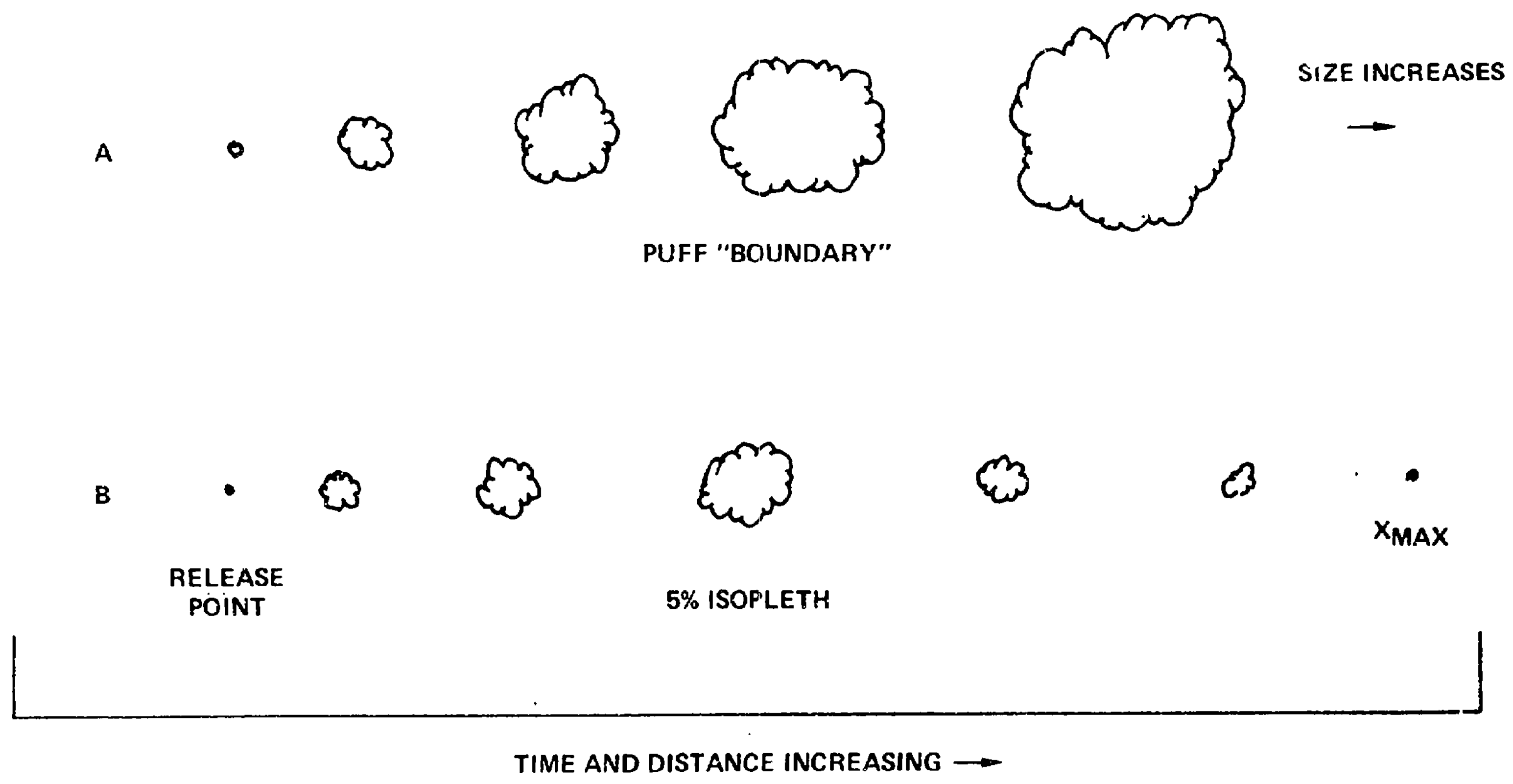
Combination of Equations V - 7 and V - 8 gives

$$C(x,y,z,t) = \frac{Q(2\pi)^{-3/2}}{\sigma_x \sigma_y \sigma_z} \exp\left[-\frac{1}{2}\left[\frac{x^2}{\sigma_x{}^2} + \frac{y^2}{\sigma_y{}^2} + \frac{z^2}{\sigma_z{}^2}\right]\right] \qquad (V-9)$$

If the diffusion process is assumed to be superimposed on (translated with) a mean wind in the x direction having velocity $\bar{u}$, a coordinate transformation gives

$$C(x,y,z,t) = \frac{Q(2\pi)^{-3/2}}{\sigma_{xI} \sigma_{yI} \sigma_{zI}} \exp\left[-\frac{1}{2}\left[\frac{(x-\bar{u}t)^2}{\sigma_{xI}{}^2} + \frac{y^2}{\sigma_{yI}{}^2} + \frac{z^2}{\sigma_{zI}{}^2}\right]\right] \qquad (V-10)$$

Equation V - 10 predicts the concentration of the gas at a position x, y, z (relative to the release point) at time t, given an <u>instantaneous point source</u> release of the gas of magnitude Q, mean wind speed $\bar{u}$, and diffusion coefficients σ_{xI} , σ_{yI} , σ_{zI} where the subscript I has been used to denote association with an <u>instantaneous</u> release. Equation V - 10 excludes all heat transfer effects, momentum transfer effects, and gravity effects associated with materials having density different from air, and can be viewed as describing the growth of a puff or cloud as it is carried downwind with the mean wind velocity $\bar{u}$, as shown in Figure V-1. Figure V-1A depicts the position of the outer limit of the cloud which continues to increase in size. Figure V-1B depicts the position of the 5% isopleth (line of constant concentration) as the cloud moves downwind. The portion of the cloud at ground level with concentration above 5% increases in size at first due to spreading of the vapors and then shrinks in size due to further dilution



PUFF DISTANCE FROM RELEASE POINT = $\bar{u}t$
WHERE t = TIME ELAPSED AFTER RELEASE

Figure V-1. GROWTH OF A PUFF (INSTANTANEOUS RELEASE OF VAPOR) WITH MEAN WIND VELOCITY $\bar{u}$

with air. At some distance downwind, labeled X_{MAX} in Figure V-1B, the entire cloud is below the 5% flammable limit. The distance X_{MAX} is presumed to be the downwind limit of the hazardous zone resulting from the spill.

Since the use of the method is dependent on the availability of the dispersion coefficients (σ_{xI}, σ_{yI}, σ_{zI}) which are determined in practice from the average behavior of a number of puffs, consideration must be given to the probability of single puffs having downwind distances (to the 5% limit) greater than X_{MAX}.

The maximum concentration predicted by Equation V - 10 occurs at the puff center ($x=\bar{u}t$, $y=o$, $z=o$). The maximum concentration at a given downwind distance is therefore given by the equation

$$c(x,y=0,\ z=0,\ t={}^{x}/\bar{u}) = \frac{Q\ (2\pi^{3})^{-1/2}}{\sigma_{xI}\sigma_{yI}\sigma_{zI}} \qquad \text{(V-11)}$$

In Equation V-11 the right hand side has been multiplied by 2 to account for the presence of the water surface.

Equation V-11 is the basic equation used by Germeles and Drake (4), the U.S. Coast Guard CHRIS model (5) and Fay and Lewis (6) for the prediction of atmospheric dispersion of LNG vapor from large rapid spills. Fay does modify the equation to force asymptotic behavior which he considers more applicable to the cloud development. The differences in

results obtained by the three groups result in part from Fay's modifications to the equation, from differences in treatment of the initial gravity controlled spread, and from use of different dispersion coefficients.
These differences will be considered in detail later in this report.

It is to be emphasized that in addition to other assumptions which eliminate consideration of heat transfer and gravity effects, Equation V - 10 applies to an instantaneous release of the gas into the atmosphere. In reality the gas cannot be released instantaneously, because the gas release rate is limited by heat transfer from the water to the spilled LNG. The rate of gas release depends on the heat transfer per unit area of LNG - water interface and on the area of LNG - water contact. Since the evaporation process is rapid due to high heat transfer rates, the gas release rate from the spreading LNG liquid pool is highly transient, with the general characteristics shown in Fig. V-2. Point A refers to the instant when a quantity of LNG is spilled on the water. The segment AB corresponds to the period of time when the liquid pool is spreading; the increase in release rate during this period is primarily due to the increase in LNG water contact area since evaporation rate per unit area of surface (for large spills) is thought to be relatively constant. At point B the liquid pool stops growing and the gas release rate remains constant until the pool begins to break up at point C.

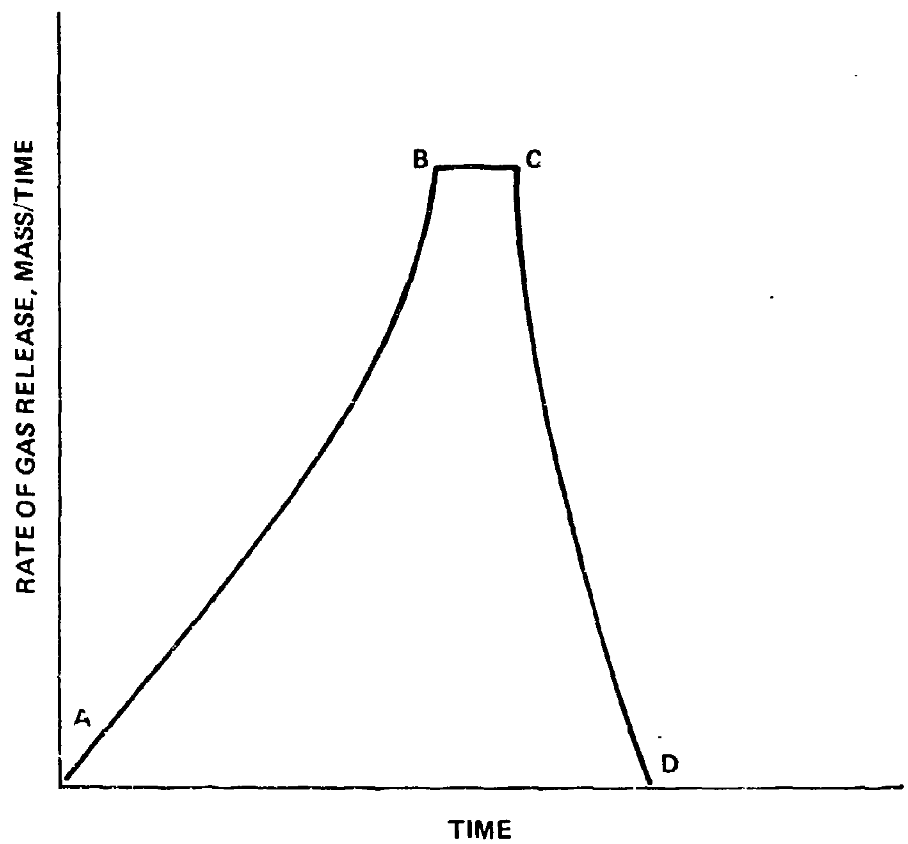


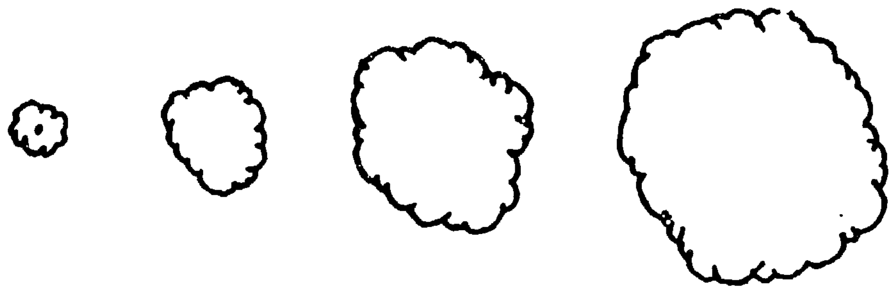
Figure V-2. PATTERN OF GAS RELEASE INTO THE ATMOSPHERE FROM AN LNG SPILL ONTO WATER

The decrease in release rate along CD corresponds to the boil off from the broken patches of LNG. At point D the release is complete.

Several LNG evaporation models (1, 2, 3, 14, 15, 16, 17, 18, 19) have been proposed for quantitative prediction of the pattern shown in Figure V-2. Some of these models have been used in predicting LNG vapor dispersion on water and will be discussed later in this report. However, the important point to be made here is that the gas release cannot be instantaneous (the use of the terminology "instantaneous spill", which implies instantaneous release of a quantity of LNG onto water has often been confused with the terminology of "instantaneous release" of gas as implied by Equation V - 10). A second feature of importance illustrated by Figure V-2 is the highly transient nature of the gas release rate. This is important because an alternative approach (to the instantaneous release model) is to model the gas release rate as being constant in time.

V-B-2. Steady Release (Plume) Model

Figure V-3 illustrates the fact that a continuous release of material can be viewed as the rapid successive release of (instantaneous) puffs. The concentration at a given point downwind resulting from a rapid succession of puffs is obtained by adding the contributions from all the puffs to the point in question. This corresponds to integration of Equation V-10 from time zero to time infinity. This integration is not straight-forward since the dispersion



TIME DEVELOPMENT OF SINGLE PUFF

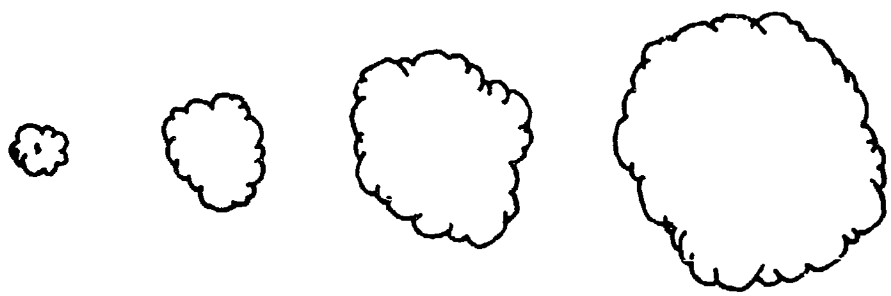
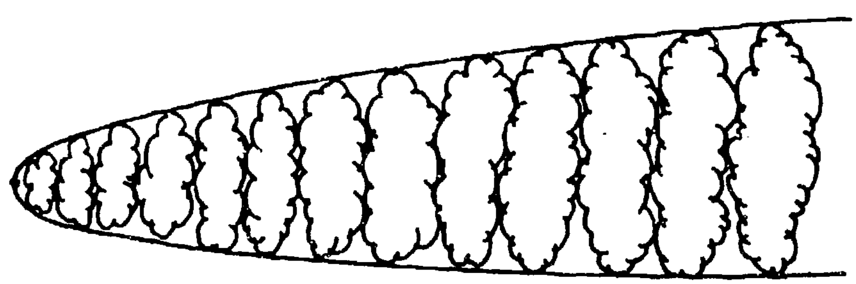


ILLUSTRATION OF SUCCESSIVE PUFFS AT AN INSTANT



RAPID SUCCESSION OF PUFFS FORMS CONTINUOUS PLUME

Figure V-3. ILLUSTRATION OF INSTANTANEOUS RELEASE OR PUFF, RELEASE OF SUCCESSIVE PUFFS, AND A CONTINUOUS RELEAS STEADY PLUME)

coefficients σ_{xI}, σ_{yI}, σ_{zI} are functions of time and distance. To simplify the model development, it is therefore commonly assumed tha. dispersion of each puff in the downwind direction is negligible in comparison with its movement associated with the mean wind velocity $\bar{u}$. The result of the time integration of the instantaneous release equation (Equation V - 10) is the equation widely used for predicting the concentration of a gas or particulate material dispersed from a ground-level point source, in a wind with mean velocity $\bar{u}$ in the X direction, at a constant rate Q':

$$C(x,y,z) = \frac{Q'}{\pi \sigma_y \sigma_z \bar{u}} \exp\left[-\frac{1}{2}\left[\frac{y}{\sigma_y}\right]^2 - \frac{1}{2}\left[\frac{z}{\sigma_z}\right]^2 \right] \qquad (V-12)$$

In Equation V - 12 the right hand side has been multiplied by 2 to account for the presence of the water surface.

Since this method is also dependent on dispersion coefficients (σ_y , σ_z) which are determined in practice from the time average behavior of a plume, consideration must be given to the probability of existence of gas pockets having downwind distances (to the 5% average value) greater than X_{MAX}.

The maximum concentration predicted by Equation V - 12 occurs at the plume center line at ground level (y = 0, z = 0). The maximum concentration at a given downwind distance is then given by the equation

$$C(x,y=0,z=0) = \frac{Q'}{\pi \sigma_y \sigma_z \bar{u}} \qquad (V-13)$$

Equation V - 13 is the basic equation used by Burgess et al. (1, 2), Feldbauer et al. (3), and the Federal Power Commission Staff (7) to model the dispersion of LNG vapors from spills onto water. The differences in results obtained by these investigators result from differences in treatment of the rate of gas addition to the atmosphere, in allowance for the effect of the "area" source, in the use of different values for the dispersion coefficients, and in modifications intended to describe heat transfer and non-uniform density effects. These differences will also be considered in detail later in this report.

Table V-2 shows a summary of the input parameters which must be specified by the user to predict downwind concentrations of vapor using Equations V - 11 and V - 13. As will be demonstrated in the detailed analyses of the various predictions that have been made using Equation V - 11 and Equation V - 13, all of the variation in the reported results can be attributed to the following factors.

1. The maximum downwind distance to the lower flammable limit concentration is strongly dependent on the amount of material released, Q, in Equation V - 11 or on the rate of addition of LNG vapor to the atmosphere, Q', in Equation V - 13.

2. The maximum downwind distance to the lower flammable limit concentration is strongly dependent on the numerical values of the dispersion coefficients, σ_{xI}, σ_{yI}, σ_{zI} used in Equation V - 11 and σ_y, σ_z used in Equation V-13. These dispersion coefficients in turn are strongly dependent on the atmospheric conditions at the spill site. Further, the specification of these dispersion coefficients in the scientific

TABLE V - 2

INPUT PARAMETERS REQUIRED FOR VAPOR DISPERSION PREDICTIONS

MODE OF RELEASE	INPUT PARAMETERS REQUIRED
Instantaneous, Point Source (Puff), Equation V-11	Q = amount released $\sigma_{xI}, \sigma_{yI}, \sigma_{zI}$ = Horizontal and vertical dispersion coefficients for instantaneous release
Steady, Point Source (Plume), Equation V-13	Q' = rate of release of material into atmosphere σ_y, σ_z = Horizontal and vertical dispersion coefficients for steady Plume $\bar{u}$ = mean wind velocity

literature is the result of actual experimental measurements (see Appendix I) from releases of material with essentially neutral buoyancy. Therefore, effects such as those associated with the low temperatures and high densities of LNG vapor are not included in literature compilations of dispersion coefficients. Various attempts, which are empirical in nature, to account for this by "doctoring" the coefficients obtained from neutrally buoyant dispersion measurements are responsible for much of the variation in predicted results based on Equation V - 11 and V - 13.

3. Equations V - 11 and V - 13 include no provisions for the LNG vapor puff or plume to spread due to gravity effects as might be expected due to the density of the cold LNG vapors. Treatment of effects resulting from gravity spreading of the vapors resulting from large spills has varied widely, with correspondingly varying results.

4. Equations V - 11 and V - 13 assume entry into the atmosphere from a point source, while an LNG spill onto water is an area source of LNG vapor. Attempts to estimate the effect of the area source, while utilizing Equations V - 11 and V - 13, are responsible for some of the variation in reported predictions of downwind vapor travel.

V - B - 3 Combined Mass, Momentum, and Energy Balance Models

A significantly different approach to the prediction of LNG vapor dispersion following an accidental spill, which involves solution of the system of Equations V-1,2,3 with less restrictive simplifying assumptions, has been published by Science Applications, Incorporated (8). This approach results in estimates of maximum

downwind distance to the lower flammable limit that are an order of magnitude shorter than some of the earlier estimates which were based on the use of Equations V-11 and V-13. A later section of this report describes in detail the methodology associated with SAI's predictions.

VI. SURVEY OF VAPOR DISPERSION PREDICTIONS ASSUMING INSTANTANEOUS RELEASE OF VAPOR FROM INSTANTANEOUS SPILL OF 25,000 M^3 OF LNG ONTO WATER - CLASSICAL PUFF MODELS

Germeles and Drake (4), the Coast Guard (5) and Fay and Lewis (6) have published predictions for a "worst case", instantaneous, release of 25,000 cubic meters of LNG onto water. Table VI - 1 is a summary of the vapor dispersion predictions obtained using the models suggested by Fay and Lewis, Germeles and Drake and CHRIS for a 25,000 M^3 instantaneous spill onto water during stable atmospheric conditions. Table VI - 2 presents results predicted for neutral weather conditions. All three groups assume applicability of Equation V - 10, the puff model, to the dispersion of the vapor following a spill. Germeles and Drake and the Coast Guard CHRIS method assume the vaporized LNG initially forms a cylindrical pancake of radius r_e and height h_e where r_e is equal to the radius of the liquid pool at the end of the evaporation period. The equations used by Germeles and Drake and the CHRIS model for predicting the radius of the pool at the end of the evaporation period (maximum pool radius) are shown in Table VI - 3. Table VI - 3 also includes, for comparison, other models for maximum pool radius which have appeared in the literature. Table VI - 4 shows the maximum pool radius, evaporation time, and height (assuming a cylindrical cloud of pure LNG vapor at its boiling point) calculated for a 25,000 M^3 spill using the equations shown in Table VI - 1.

TABLE VI - 1

LNG VAPOR DISPERSION PREDICTIONS FOR 25,000 M^3
INSTANTANEOUS SPILL - BASED ON CLASSICAL PUFF
MODEL - STABLE WEATHER CONDITIONS

	FAY AND LEWIS (6)	GERMELES AND DRAKE (4)	CHRIS (5)
I. Initial Pure Vapor Cloud Size*	Not applicable	Radius = 383 M*	Radius = 383 M*
	Not applicable	Height = 13 M	Not applicable
II. Vapor Cloud Size at End of Gravity Spread Phase	Radius = 816 M	Radius = 950 M	Not applicable
	Height = 2.9 M**	Height = 22.6 M	Not applicable
III. Concentration of Vapor Cloud at End of Gravity Spread Phase	100%	22% (by volume)***	Not applicable
IV. Maximum Downwind Distance to 5% (average) Concentration	17.4 Miles (1)	11.5 Miles (2)	16.3 Miles (3)
V. Maximum Downwind Distance to 2.5% (average) Concentration	31.0 Miles (1)	22.1 Miles (2)	24.4 Miles (3)

* Initial cloud radius assumed equal to radius of pool at end of vaporization period

** This value of cloud height assumes the cloud to be at the LNG boiling temperature

*** Assumes mean wind velocity of 5 MPH

(1) Fay's Model, using "Very Stable" Puff Dispersion Coefficients from Slade (13) (Appendix I) - If a neutrally buoyant or ambient temperature cloud is assumed at the end of the gravity spread phase, a greater distance results.

(2) G-D Model, using Gifford-Pasquill "F-Moderately Stable" Plume Dispersion Coefficients (Appendix 1)

(3) CHRIS Model, using Gifford-Pasquill "F-Moderately Stable" Plume Dispersion Coefficients (Appendix 1)

TABLE VI - 2

LNG VAPOR DISPERSION PREDICTIONS FOR 25,000 M^3
INSTANTANEOUS SPILL - BASED ON CLASSICAL PUFF
MODEL - NEUTRAL WEATHER CONDITIONS

	FAY AND LEWIS (6)	GERMELES AND DRAKE (4)	CHRIS (5)
I. Initial Pure Vapor Cloud*	Not applicable	Radius = 383 M*	Radius = 383 M
		Height = 13 M	Not applicable
II. Vapor Cloud Size at End of Gravity Spread Phase	Radius = 816 M	Radius = 950 M	Not applicable
	Height = 2.9 M	Height = 22.6 M	Not applicable
III. Concentration of Vapor Cloud at End of Gravity Spread Phase	100%	22% (by volume)**	Not applicable
IV. Maximum Downwind Distance to 5% (average) Concentration	1.6 Miles (1)	3.0 Miles (2)	3.2 Miles (3)
V. Maximum Downwind Distance to 2.5% (average) Concentration	3.0 Miles (1)	5.6 Miles (2)	4.8 Miles (3)

* Initial cloud radius assumed equal to radius of pool at end of vaporization period

** This value of cloud height assumes the cloud to be at the LNG boiling temperature

*** Assumes mean wind velocity of 5 MPH

(1) Fay's Model, using Neutral Puff Dispersion Coefficients from Slade (13) (Appendix 1) - If a neutrally buoyant or ambient temperature cloud is assumed at the end of the gravity spread phase, a greater distance results

(2) Germeles and Drake Model, using Gifford-Pasquill "D-Neutral" Plume Dispersion Coefficients (Appendix 1)

(3) CHRIS Model, using Gifford-Pasquill "D-Neutral" Plume Dispersion Coefficients (Appendix 1)

TABLE VI - 3

PUBLISHED MODELS FOR PREDICTING EVAPORATION TIME AND MAXIMUM POOL SIZE FOR INSTANTANEOUS SPILLS OF LNG ONTO WATER

EQUATION FOR MAXIMUM RADIUS	EQUATION FOR EVAPORATION TIME	SOURCE
(1) $r_e = \dfrac{7.4\ V^{3/8}}{h^{1/4}}$	$t_e = \dfrac{8.8\ V^{1/4}}{h^{1/2}}$	Raj/Kalelkar (15) (used by Germeles-Drake and CHRIS)
(2) $r_e = 4.7\ V^{5/12}$	$t_e = 3.3\ V^{1/3}$	Fay (14)
(3) $r_e = 10.4\ V^{5/12}$	$t_e = 14.5\ V^{1/3}$	Hoult (16)
(4) $r_e = 7.3\ V^{3/8}$	$t_e = 7.9\ V^{1/4}$	Hoult (17)
(5) $r_e = \dfrac{7.6\ V^{3/8}}{h^{1/8}}$	$t_e = \dfrac{12.4\ V^{1/4}}{h^{1/2}}$	Otterman (18)
(6) $r_e = \dfrac{9.07\ V^{3/8}}{h^{1/4}}$	$t_e = \dfrac{10.56\ V^{1/4}}{h^{1/2}}$	Muscari (19)

where V = Volume of Spill, ft^3 LNG

r_e = Maximum Pool Radius, ft

t_e = Evaporation Time, sec

h = Liquid Regression Rate, in/min

TABLE VI - 4

PREDICTION OF INITIAL LNG VAPOR CLOUD SIZE FOLLOWING INSTANTANEOUS SPILL OF 25,000 M^3 ON WATER USING MODELS OF TABLE VI-I

SOURCE	VAPOR CLOUD RADIUS (FT)	EVAPORATION TIME (SEC)	VAPOR CLOUD HEIGHT (FT)*
Raj/Kalelkar (15) (used by Germeles-Drake and CHRIS)	1255	270	43
Fay (14)	1417	316	34
Hoult (16)	3136	1390	7
Hoult (17)	1239	242	44
Otterman (18)	1289	380	41
Muscari (19)	1539	324	29

* Vapor Cloud Height = 241 $V_{liq}/\pi r_e^2$

where $241 = \dfrac{\text{Gas Specific Volume at Boiling Point}}{\text{Liquid Specific Volume at Boiling Point}}$

Fay and Lewis and Germeles and Drake assume the vapor generated, being heavier than air, will spread laterally across the water surface. Fay assumes the cloud spreads without appreciable mixing with air, while Germeles and Drake allow for air entrainment at the top of the cloud. The termination of the so-called "gravity spread" phase was considered by Fay and Lewis to be the point where the cloud becomes neutrally buoyant due to heat transfer from the water below the cloud. Germeles and Drake terminated this phase of their model at the point where the cloud becomes buoyant under no wind conditions, or when wind is present, at the point where the gravity spread velocity of the cloud equals the mean wind velocity. Fay models the "warming up" process of the cloud as resulting only from convective heat transfer between the water surface and the cloud, while Germeles and Drake consider heat effects due to convection and mixing with entrained air, including the latent heat effects of condensation and freezing of water vapor. The vapor cloud at the end of the gravity spread phase, as described by Fay and Lewis and Germeles and Drake in Items II and III in Table VI - 1, are used as starting points for their models of the atmospheric dispersion phase. All three use vapor dispersion models based on Equation V - 10, restated:

$$C(x,y,z,t) = \frac{Q(2\pi)^{-3/2}}{\sigma_{xI}\sigma_{yI}\sigma_{zI}} \exp\left[-\frac{1}{2}\left[\frac{(x-\bar{u}t)^2}{\sigma_{xI}^2}+\frac{y^2}{\sigma_{yI}^2}+\frac{z^2}{\sigma_{zI}^2}\right]\right] \quad \text{(VI-1)}$$

VI-A. PREDICTIONS USING FAY'S MODEL

Fay notes that the maximum concentration at any point downwind must occur at ground level at the cloud (puff) center, or $x=\bar{u}t$, $y=0$, $z=0$, and he assumes $\sigma_{yI} = \sigma_{xI}$. Both assumptions are widely practiced and appear to be justified within the error of existing experimental data when other assumptions of the model (neutral buoyancy, dilute pollutant/air concentrations) are valid.

Equation VI -1 then becomes

$$C_m = \frac{Q}{(2\pi^3)^{1/2} \sigma_{yI}^2 \, \sigma_{zI}} \qquad \text{(VI - 2)}$$

where the subscript $_m$ denotes "maximum"

In Equation VI - 2 the right hand side has been multiplied by 2 to account for the presence of the water surface. Since Q is the amount of LNG vapor added (instantaneously, according to the development of Equation V - 1) and the cloud is assumed to be pure at the end of the gravity spread phase, Fay substitutes

$$Q = \pi \, r_{vm}^2 \, h_v$$

where r_{vm} and h_v are the radius and height of the pure vapor cloud to get

$$C_m = \frac{1}{(2\pi)^{1/2}} \left[\frac{r_{vm}}{\sigma_{yI}}\right]^2 \left[\frac{h_v}{\sigma_{zI}}\right] \qquad \text{(VI - 3)}$$

Equation VI - 3 includes the effect of horizontal and vertical mixing. Fay argues that horizontal mixing would be suppressed near the spill due to the shallow depth of the cloud. He assumes that near the spill only vertical mixing would occur and that the resulting vertical distribution would be Gaussian. Hence at these "intermediate" distances Fay argues that the maximum ground level concentration would be

$$C_m = \left[\frac{2}{\pi}\right]^{1/2} \left[\frac{h_v}{\sigma_{zI}}\right] \qquad \text{(VI - 4)}$$

Finally, Fay argues that at the location of the spill the concentration must be unity (i.e. 1 FT^3 of LNG vapor per FT^3 of space). Based on consideration of Equations VI-3 and VI-4 and the requirement of unity concentration at the source, Fay proposed the following modified form of Equation VI - 1, which asymptotically yields $C_m = 1$ at the spill location, Equation VI - 4 at intermediate distances (where $\sigma_{yI} << r_{vm}$ and $\sigma_{zI} >> h_v$) and Equation VI - 3 at large distances from the spill source (where $\sigma_{yI} >> r_{vm}$ and $\sigma_{zI} >> h_v$):

$$C_m = \left[\frac{r_{vm}}{r_{vm} + \sqrt{2}\sigma_{yI}}\right]^2 \left[\frac{h_v}{h_v + \left[\frac{\pi}{2}\right]^{1/2} \sigma_{zI}}\right] \qquad \text{(VI - 5)}$$

Since Fay wanted to compare his model prediction with the experimental data reported by Feldbauer (3), he assumes that at large distances from the spill the time average concentration,

$\bar{C}$, of a passing cloud is given by

$$\bar{C} = \frac{C_m}{2}$$

The equation for $\bar{C}$ corresponding to Equation VI - 5 then becomes

$$\bar{C} = \left[\frac{r_{vm}}{r_{vm} + 2\,\sigma_{yI}}\right]^2 \left[\frac{h_v}{h_v + \left[\frac{\pi}{2}\right]^{1/2} \sigma_{zI}}\right] \qquad \text{(VI - 6)}$$

Fay compares results obtained from his analysis of Feldbauer's data with the prediction of Equation (VI - 6) and obtains rough agreement.

In order to define the maximum downwind flammable extent of the cloud, we are primarily interested in the prediction of the distance at which $C_m = 0.05$ (or some fraction thereof, depending on assumptions of peak-to-average concentration ratio) as predicted by Equation VI - 5. In order to solve for this distance, the dispersion coefficients σ_{yI} and σ_{zI} must be specified as functions of the downwind distance. Fay assumes σ_{yI} and σ_{zI} to be given by the following equations (see Appendix I).

	Neutral Stability	Very Stable	
σ_{yI}	$0.06\ x^{0.92}$	$0.02\ x^{0.89}$	
σ_{zI}	$0.15\ x^{0.70}$	$0.05\ x^{0.61}$	(VI - 7)

where σ_{yI} , σ_{zI} , x are in meters

Equations VI - 7 are estimated correlations for instantaneous - source values of σ_{yI} and σ_{zI} given by Slade (13) and are based largely on the data of Hogstrom (20). The correlations for the "very stable" condition denote the approximate limit of the "most stable" data of Hogstrom.

The solution of Equation VI - 5 for C_m as a function of x, the downwind distance, assuming "very stable" coefficients, is shown in Figure VI - 1 for a 25,000 M^3 instantaneous LNG spill. From Figure VI - 1, the distance to a maximum concentration of 5% is predicted to be 25,000 meters. The distance to C_m = 0.025 (incorporating a 2 to 1 peak-to-average ratio) is 50,000 meters. The distance to C_m = 0.01 (incorporating a 5 to 1 peak-to-average ratio) is 100,000 meters.

Values for r_{vm} and h_v of 816 meters and 2.9 meters respectively were used in the calculation of downwind distances shown in Figure VI - 1 and Tables VI - 1 and VI - 2. These values were taken from Lewis' thesis (40). The values of 2.9 meters for h_v and 816 meters for r_{vm} correspond to a pure vapor cloud volume at the LNG boiling point, approximately 240 times the spilled liquid volume. Although Fay and Lewis' paper indicates (on the last line of page 491 in Reference 6) that a pancake <u>neutrally buoyant</u> pure vapor cloud of radius r_{vm} and height h_v forms over the spill, the results which appear in Lewis' thesis and which correspond to Figure 5 of Fay and Lewis' paper apparently are based on values of r_{vm} and h_v of 816 meters and 2.9 meters respectively. If the height of the cloud is determined from

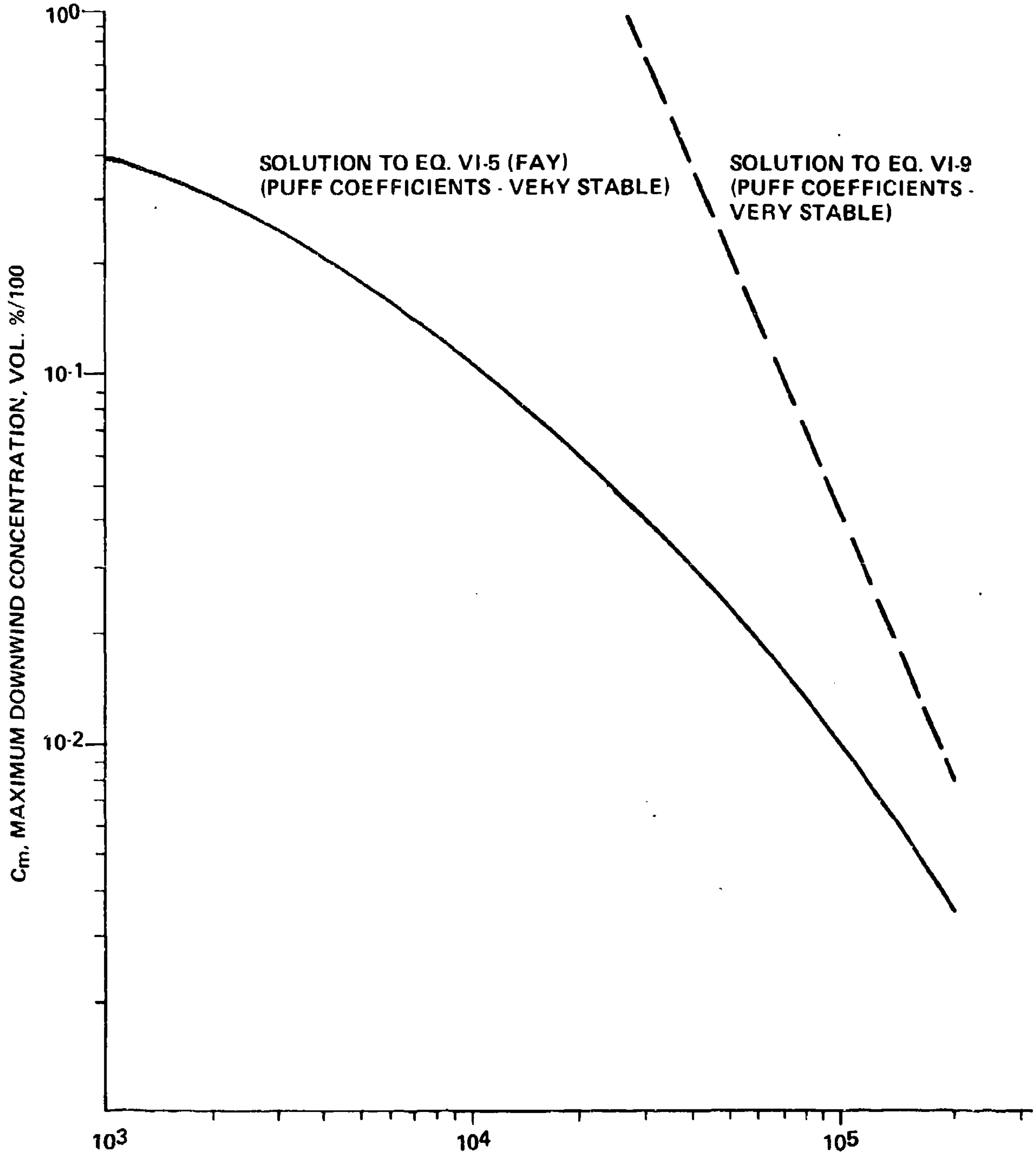


Figure VI-I. DOWNWIND CONCENTRATION AS A FUNCTION OF DISTANCE FROM 25,000 CUBIC METER SPILL ONTO WATER – FAY'S MODEL

the volume at the temperature corresponding to neutral buoyancy (∿-155F) the height is increased by a factor of about 1.45 and the predicted downwind distance with very stable weather increases to approximately 23 miles. In a recent communication, Dr. Fay suggests that the h_v should be determined from the volume of the pure gas cloud at $0^{o}C$. In this case h_v is estimated to be 7.1 meters and the downwind distance to the 5% level with stable weather conditions is calculated to be 28.0 miles. (See Appendix II)

Fay's rationale for the development of Equation VI - 5 included the requirement that it agree, at long distances, with Equation VI - 3, restated

$$C_m = \frac{1}{(2\pi)^{1/2}} \left[\frac{r_{vm}}{\sigma_{yI}}\right]^2 \left[\frac{h_v}{\sigma_{zI}}\right] \qquad \text{(VI - 8)}$$

Recalling that

$$V = \pi r_{vm}{}^2 h_v$$

where V = volume of gas released

r_{vm} = radius of pure gas cloud at end of gravity spread phase

h_v = height of pure gas cloud at end of gravity spread phase,

Equation VI - 8 is equivalent to

$$C_m = \frac{V}{(2\pi^3)^{1/2} \ \sigma_{yI}{}^2 \ \sigma_{zI}} \qquad \text{(VI - 9)}$$

Note that Equation VI - 9 is just the equation for the maximum downwind concentration (ground level, z = 0, and cloud center,

y = 0) for a puff or instantaneous release of vapor volume V. The solution of Equation VI - 9 is plotted in Figure VI - 1 for comparison with Equation VI - 5, using σ_{yI} , σ_{zI} suggested by Slade for "very stable" atmospheres. Although Fay's model (Equation VI - 5) approaches the solution to Equation VI - 9 for very long distances, the distances predicted for 5% concentration (lower flammable limit for methane) for a 25,000 cubic meter spill is significantly different for the two equations (by a factor of 3.7). The important point to be made is that Fay's model can be viewed as a model for the point source instantaneous release of 25,000 M^3 LNG as vapor, modified to give a finite concentration (C_m = 1) at the source.

VI-B. PREDICTIONS USING GERMELES AND DRAKE'S MODEL

Although the final prediction of downwind distance to a given concentration by Germeles and Drake is also based on the use of Equation VI - 1, the classical diffusion model for the dispersion of a "puff" (instantaneous release of vapor), other procedures in their model differ significantly from those of Fay:

1. Germeles and Drake allow for entrainment of air by the LNG cloud as it spreads across the water surface immediately following the release (which is treated as if the vapor release is instantaneous). This results in a cloud which is to be used as the start of the dispersion phase (to be described by Equation VI - 1) that is already diluted with air.

2. Germeles and Drake terminate the initial gravity spread phase of the cloud (during which time air is entrained) at the point where it reaches neutral density under no-wind conditions or when the velocity of the edge of the spreading cloud falls to the mean wind velocity.

3. Germeles and Drake argue that an analysis of Hogstrom's data for dispersion coefficients for instantaneous release do not justify Slades' estimated correlation, particularly for "very stable" weather:

$$\sigma_{yI} = 0.02 \ x^{0.89}$$

$$\sigma_{zI} = 0.05 \ x^{0.61}$$

Instead, they recommend the use of the Pasquill F stability "plume" dispersion coefficients for stable weather and Pasquill D stability coefficients for neutral weather conditions.

4. Since Drake and Germeles assume a "starting point" cloud of 22% vapor (specific to the case being considered) for the atmospheric dispersion prediction, they correct the result predicted by Equation VI -1 by subtracting the distance required for a 22% concentration to occur downwind of a point source instantaneous release. This method, usually referred to as the specification of a "virtual source", is a common practice for allowing for the effect of an area source. The method is illustrated

in Figure VI - 2, where X is the distance computed for $C_m = 0.05$ using Equation VI - 1 and X_v is the distance computed for $C_m = 0.22$. The downwind distance to $C_m = 0.05$ from the actual (area) source is then

$$X' = X - X_v \qquad \text{(VI - 10)}$$

As shown in Table VI - 1, the size of the initially formed pure LNG vapor cloud over the spill has a radius of 383 meters and a height of 13 meters. Germeles and Drake assume that during the gravity induced spread the cloud can be represented by its average spatial thermodynamic state. That is, the cloud at any instant is assumed uniform in temperature and composition.

The equation used to predict the gravity spread of the vapor cloud was proposed by Yih (22) to describe density intrusion weather phenomena such as the movement of cold fronts:

$$\frac{dR}{dt} = \left[kg \left[\frac{\rho - \rho_a}{\rho_a}\right] H \right]^{1/2}$$

$$= 29.11 \left[(\rho - 0.076)\ H \right]^{1/2} \qquad \text{(VI - 11)}$$

where H = cloud height, ft

t = time, sec

ρ = cloud density, lb/ft^3

k = 2

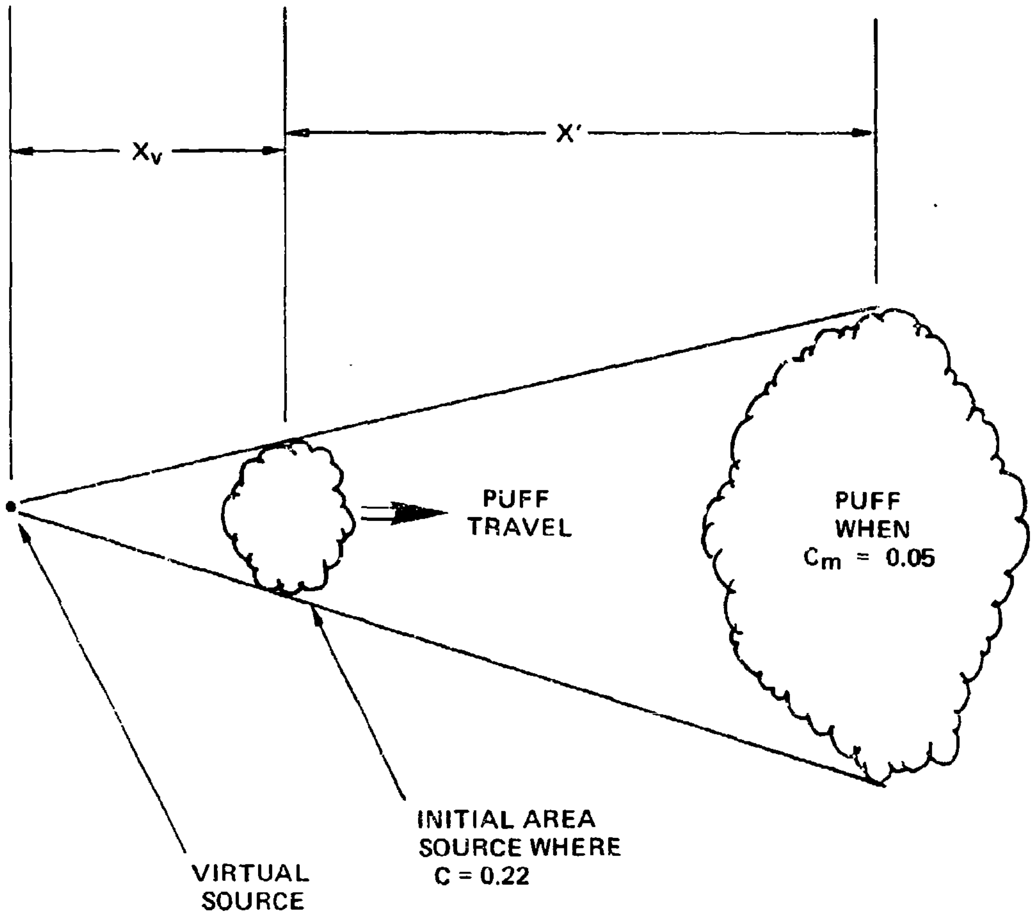


Figure VI-2. ILLUSTRATION OF VIRTUAL SOURCE LOCATION FOR "AREA SOURCE" CORRECTION

The cloud density, ρ, varies due to air entrainment and heat transfer between the cloud and its surroundings.

Germeles and Drake assume that air is entrained at the upper surface of the spreading LNG cloud as the clouds spread laterally. If the volume of air entrained, $d\dot{Q}_e$, by an annular area, $2\pi r dr$, of the top surface of the cloud is

$$d\dot{Q}_e = \alpha\, U_c\, 2\pi r dr \qquad \text{(VI - 12)}$$

where U_c = local velocity of the cloud surface $\left[\text{assumed} = \frac{r}{R} \frac{dR}{dt}\right]$

α = entrainment coefficient

then

$$\begin{aligned} d\dot{Q}_e &= \alpha \frac{r}{R}\, 2\pi r dr \frac{dR}{dt} \\ &= \frac{2\pi\alpha}{R} \frac{dR}{dt} r^2 dr \end{aligned} \qquad \text{(VI - 13)}$$

Integrating from $r = 0$ to $r = R$,

$$\dot{Q}_e = \frac{2\pi\alpha R^2}{3} \frac{dR}{dt} \qquad \text{(VI - 14)}$$

From the principle of mass conservation,

$$\frac{dM}{dt} = \rho_a \dot{Q}_e \qquad \text{(VI - 15)}$$

where M = mass of the "mixed" cloud

From the energy conservation principle,

$$\frac{d(MCT)}{dt} = C_a \rho_a \dot{Q}_e T_a + \dot{Q}_v + \dot{Q}_w \qquad \text{(VI - 16)}$$

where
C = heat capacity of mixed cloud
T = temperature of mixed cloud
a = refers to air only
$\dot{Q}_v$ = heat of condensation and freezin of water in cloud
$\dot{Q}_w$ = heat transferred by convection, natural ($\dot{Q}_n$) or forced ($\dot{Q}_f$), whichever is greater

$$\dot{Q}_n = 1.1 \times 10^{-4} \; \pi R^2 \; (T_w - T)^{4/3}$$

$$\dot{Q}_f = \frac{f}{2^{\alpha}} \; C\rho \; \dot{Q}_e \; (T_w - T) \qquad \text{(VI - 17)}$$

Solution of the four simultaneous equations;

$$\frac{dR}{dt} = 29.11 \; (\rho - 0.076)^{1/2} \; H^{1/2} \qquad \text{(VI - 18)}$$

$$\frac{dM}{dt} = \rho_a \; \frac{2\pi}{3} \alpha \; R^2 \; \frac{dR}{dt} \qquad \text{(VI - 19)}$$

$$\frac{d(MCT)}{dt} = C_a \rho_a \dot{Q}_e T_a + \dot{Q}_v + \dot{Q}_w \qquad \text{(VI - 20)}$$

$$M = \pi R^2 H \rho \qquad \text{(VI - 21)}$$

gives the concentration and temperature development of the cloud during the gravity spreading phase.

Figures VI - 3 and VI - 4 show the development of the cloud radius (R), temperature (T), height (H) and concentration (C) for a 25,000 M^3 instantaneous spill, using Germeles and Drakes' gravity spread model. The initial temperature and humidity of the air and the values used for α, the entrainment coefficient, and f, the friction factor in Equation VI - 17, are also shown in Figures VI - 3 and VI - 4.

Solution of Equation VI - 1 for y = z = 0 and x = $\bar{u}$t gives

$$C_M = \frac{Q}{(2\pi^3)^{1/2} \sigma_{yI}^2 \sigma_{zI}} \qquad \text{(VI - 22)}$$

Q in Equation VI - 22 was assumed by Germeles and Drake to be the volume of the pure vapor cloud formed at ambient conditions (70^oF, 1 atm) or approximately 630 times the spilled liquid volume. Solving Equation VI - 22 by trial and error, using the Gifford Pasquill correlations for σ_y, σ_z vs X (Appendix I) for "D-Neutral" weather for C_m = 0.22 gives $X_V \sim 5000$ meters. Solving Equation VI - 22 similarly for C_m = 0.05 gives X $\cong$ 9800

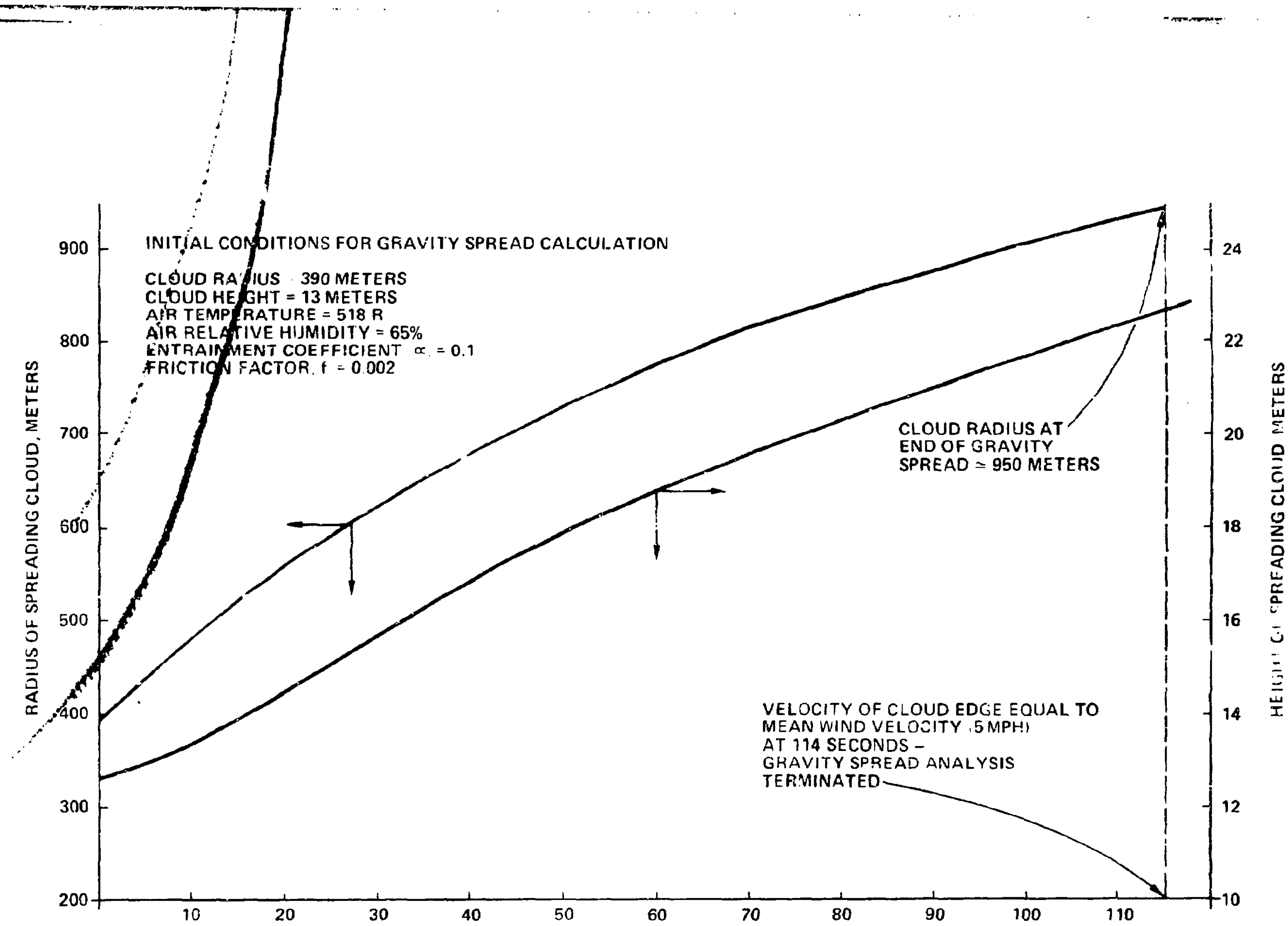


Figure VI-3. CLOUD RADIUS AND HEIGHT vs. TIME, GRAVITY SPREAD PHASE (GERMELES AND DRAKE)

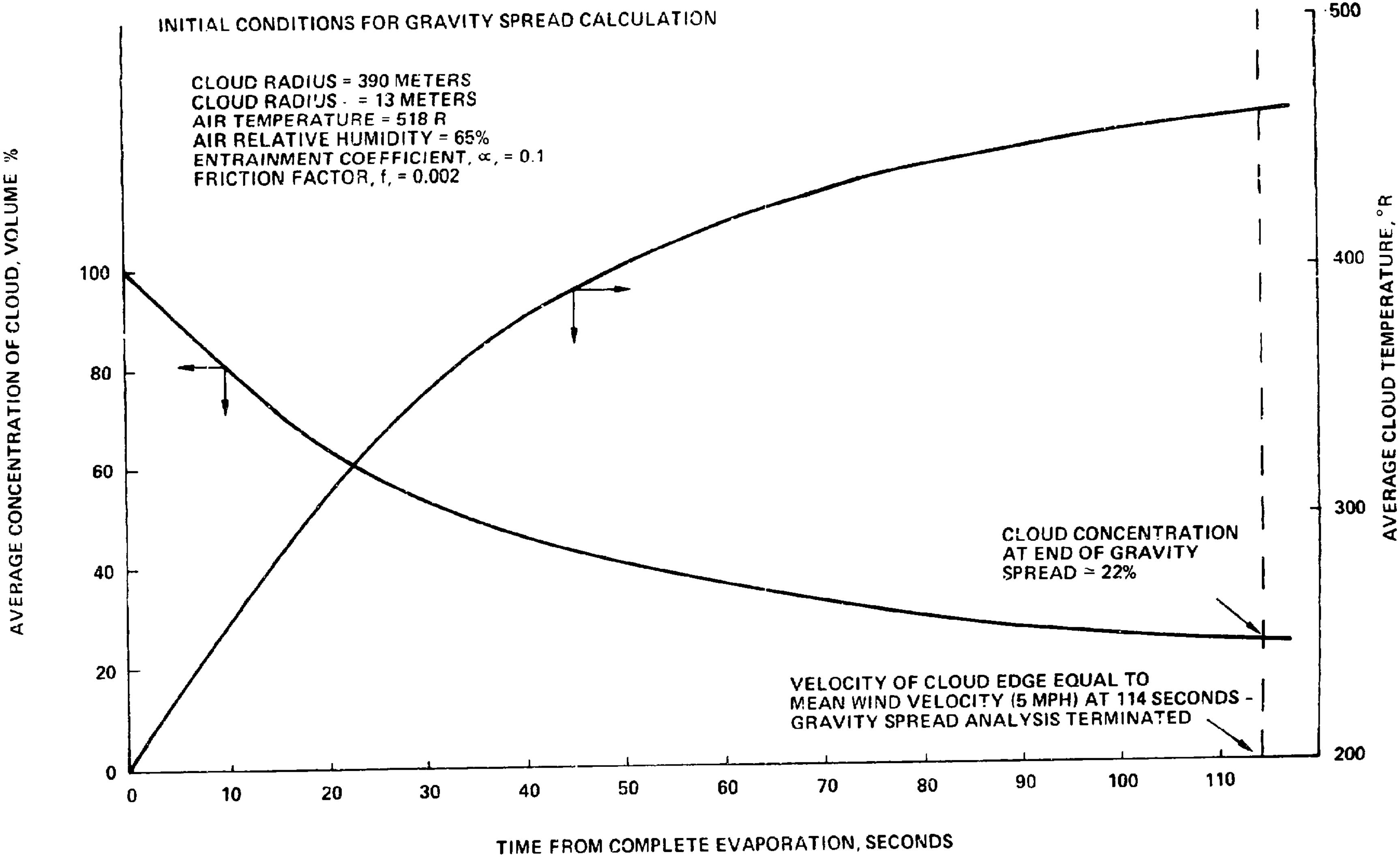


Figure VI-4. CLOUD CONCENTRATION AND TEMPERATURE vs. TIME, GRAVITY SPREAD PHASE (GERMELES AND DRAKE)

meters. The downwind distance to 5% concentration for neutral stability conditions is then 9800 - 5000 = 4800 meters (3.0 miles) as shown in Table VI - 2. A similar calculation shows the distance to the 5% concentration for moderately stable (F) conditions to be about 10,000 meters (∿11.5 miles) as shown in Table VI - 1.

Calculations were made to determine the effect of variation in α , the entrainment coefficient, on the downwind distance to the LFL as predicted by Germeles and Drake. Figure VI - 5 shows the average concentration of the cloud during the gravity spread phase for values of α of 0.01, 0.05, 0.1, 0.20, and 0.50. The first vertical hash-mark on each α curve on Figure VI-5 denotes the time (and concentration) when the gravity spread phase would be terminated for a 10 MPH wind. The second vertical hash-mark on each α curve denotes the time (and concentration) when the gravity spread phase would be terminated for a 5 MPH wind. For $\alpha = 0.5$, the downwind concentration drops below 5% before the cloud edge velocity decreases to 5 MPH and before the cloud becomes neutrally buoyant.

VI - C. <u>PREDICTIONS USING U.S. COAST GUARD (CHRIS) MODEL (5)</u>

The U.S. Coast Guard has published methods for estimating downwind dispersion of vapors from spills of LNG or other cryogenic liquids in its "CHRIS" - Chemical Hazards Reponse

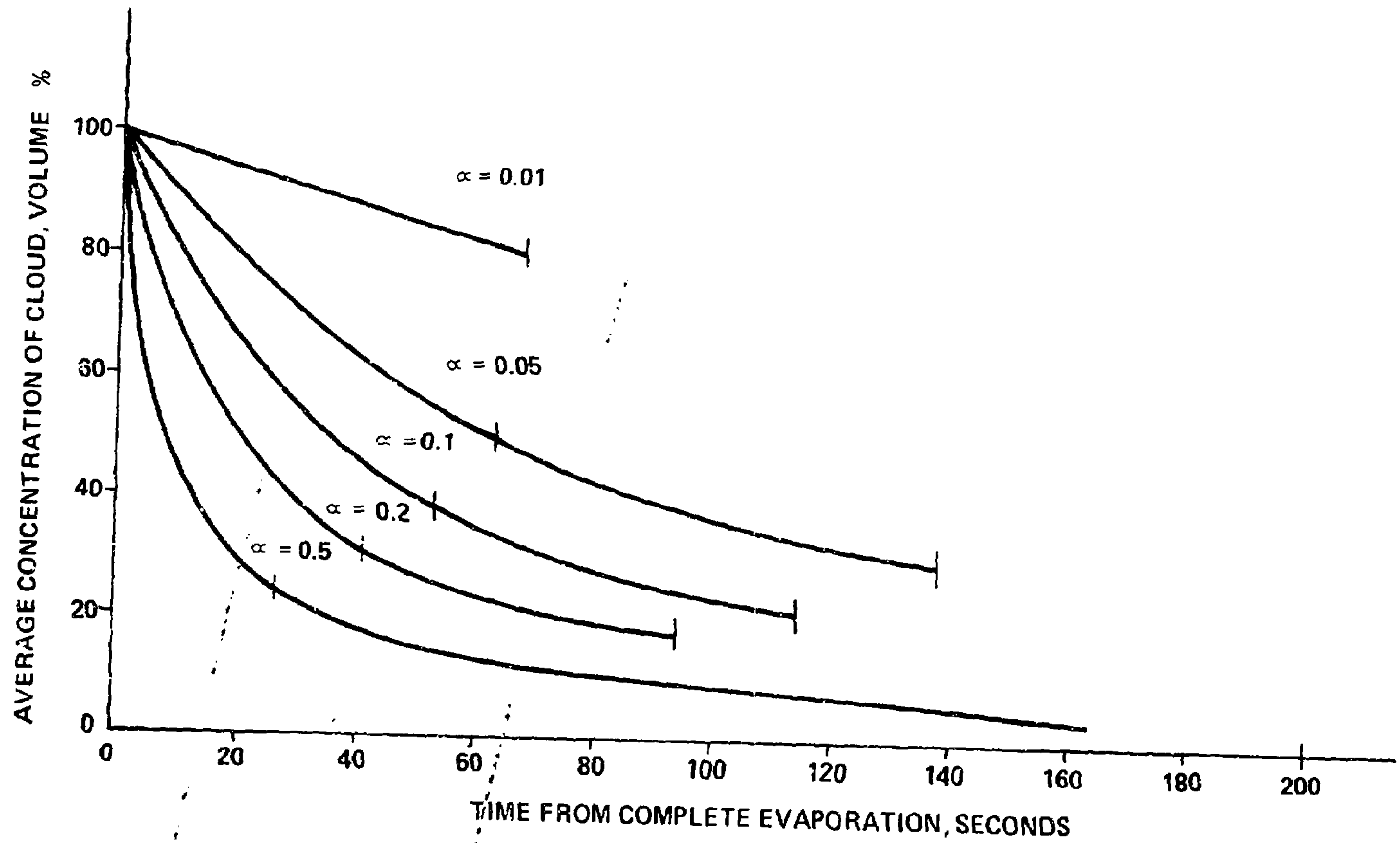


Figure VI-5. EFFECT OF ENTRAINMENT COEFFICIENT ON GRAVITY SPREAD

System. These methods were developed by Arthur D. Little, Inc. under contract to the Coast Guard. ADL's model for vapor dispersion from an instantaneous LNG spill, as incorporated in CHRIS, is also based on Equation VI - 1, the classical diffusion model for the dispersion of a "puff" (instantaneous release of vapor).

To determine the downwind distance to the 5% (average) concentration, Equation VI - 1 was simplified for the ground level, centerline case (x = ut, y = 0, z = 0)

$$C_m = \frac{Q}{(2\pi^3)^{1/2} \sigma_{yI}^2 \sigma_{zI}} \qquad \text{(VI - 23)}$$

In Equation VI - 23 the right side has been multiplied by 2 to account for the presence of the water surface.

For a 5 MPH wind and stable weather conditions, values of the downwind distance are assumed until Equation VI - 23 predicts 5% concentration. The dispersion coefficients for stable weather conditions are taken from the Pasquill plume dispersion coefficient charts shown in Appendix I. It was recognized by ADL (5) that the application of these coefficients to the dispersion of a puff (instantaneously released vapor) is debatable, but such use was recommended until more experimental data are available. Using the coefficients representing Pasquill F stability, the downwind distance to the 5% (average) concentration is determined (by trial and error) to be approximately 30,000 meters.

The CHRIS model accounts for the area source nature of an evaporating LNG pool by locating a virtual source at a distance 5 pool diameters upwind of the center of the pool as shown in Figure VI - 6. The liquid pool diameter is estimated using the maximum pool radius model proposed by Raj and Kalelkar (15) shown in Table VI - 3, restated:

$$r_e = 7.4 \frac{V^{3/8}}{h^{1/4}} \qquad \text{(VI - 24)}$$

where V = volume of spill, ft^3 LNG

r_e = Maximum Pool Radius, ft

h = Liquid Regression Rate, in /min

For a 25,000 cubic meter instantaneous spill, Equation VI - 24 gives a maximum pool diameter ($2r_e$) of 766 meters. The distance between the pool center and the virtual source is then 5 pool diameters, or 3830 meters. Subtracting this distance from the result given by Equation VI - 23, the downwind distance is 26,200 meters or 16.3 miles, as shown in Table VI - 1.

The CHRIS model described above assumes the instantaneously formed cloud to be at ambient temperature and pressure ($70^{\circ}F$, 1 atm), and there is no provision for gravity spreading or heat transfer effects.

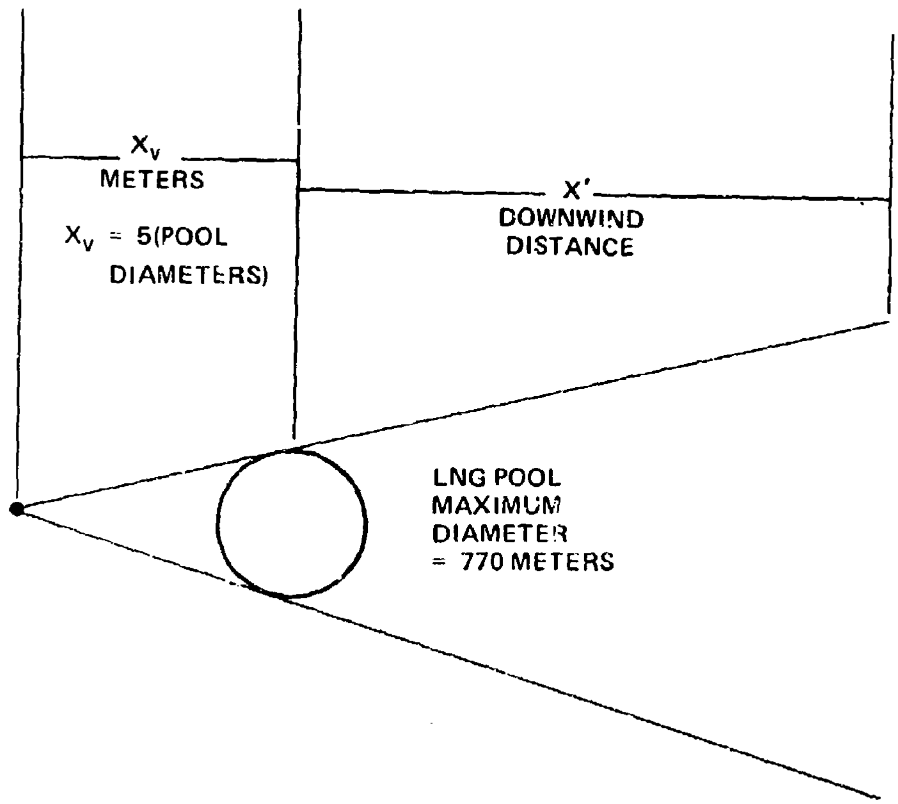


Figure VI-6. SCHEMATIC OF LNG POOL AND LOCATION OF VIRTUAL POINT SOURCE FOR 25,000 M^3 INSTANTANEOUS SPILL AS SUGGESTED BY ADL, INC. IN CHRIS MODEL

VI-D COMPARISON OF RESULTS BASED ON INSTANTANEOUS VAPOR RELEASE MODELS

The predictions shown in Table VI - 1 and VI - 2 by Germeles and Drake, Fay, and CHRIS of maximum downwind distance to the 5% and 2 1/2% time-average vapor concentration following instantaneous release of 25,000 M^3 of LNG as vapor during neutral and stable atmospheric conditions appear to indicate fair agreement. The maximum variation is about 25% from the mean value for the downwind distance to the 5% vapor concentration during stable weather conditions. However, this "agreement" is due to compensating differences in the approaches.

The gravity spread portion of the Germeles and Drake model determines the concentration which is assumed to represent the starting point for dispersion resulting from atmospheric turbulence. This estimated concentration (22% for the conditions chosen for illustration) directly determines the virtual source correction as indicated in Figure VI - 2. The virtual source distance (X_V of Figure VI - 2) for a 25,000 cubic meter instantaneous release during stable weather conditions, using the Germeles and Drake model, is approximately 14,000 meters or 8.5 miles. The CHRIS model, however, estimates the virtual source distance to be five pool diameters or approximately 3,800 meters (~2.4 miles). Since the estimation techniques do not differ except in estimating the virtual source distance, the difference in predictions by CHRIS and Germeles-Drake can be directly attributed to the greater virtual source correction resulting

from the gravity spread effects included in the Germeles Drake model.

A "comparison" of the predictions of the Germeles and Drake and Fay models is more difficult. Four factors affecting the predictions of these models must be recognized.

1. Fay's modification of the classical dispersion equation to force a unity concentration at the source tends to shorten his predicted distances in comparison to the results obtained with simple application of the puff model (as shown in Figure VI - 1) and the model of Germeles and Drake.

2. Fay's model has been used in this report assuming the total vapor volume released from the spill to be the saturated vapor volume of LNG at 1 atmosphere pressure, or approximately 240 times the liquid volume. The total volume of vapor released from the spill is assumed in the Germeles and Drake predictions to be the volume of methane at standard conditions (70°F, 1 atm) or approximately 630 times the liquid volume. If the larger volume is used in Fay's model, as suggested by Fay in a recent communication to this author (see Appendix 2, Fay's comments), a much longer distance ($\sim$28 miles) results.

3. Fay uses the "very stable" category puff dispersion coefficients presented by Slade. Germeles and Drake argue in their paper that the very stable puff dispersion coefficients correlation suggested by Slade is not sufficiently justified from an analysis of the original data,

and that the Pasquill F stability coefficients which represent "plume" dispersion data are more applicable in their analysis. This choice, however, considerably shortens the downwind distance to the 5% level when using the Germeles and Drake model. If the very stable puff dispersion coefficients of Slade are used in Germeles and Drake's model the calculated distance to the 5% level shown in Table VI - 1 would be approximately 40 miles. Conversely, if the Pasquill F stability coefficients are used in Fay's model instead of the very stable puff coefficients cited by Slade, the predicted distance is cut roughly in half as shown in Figure VI - 7.

4. Fay's model does not address the possibility of air entrainment during the gravity spread. This factor considered alone would tend to give a longer distance using the Fay model than the Germeles and Drake model.

In view of these important differences in the three models, particularly the differences between the Germeles and Drake and Fay models, the "agreement" indicated in Table VI - 1 and Table VI - 2 must be considered fortuitous.

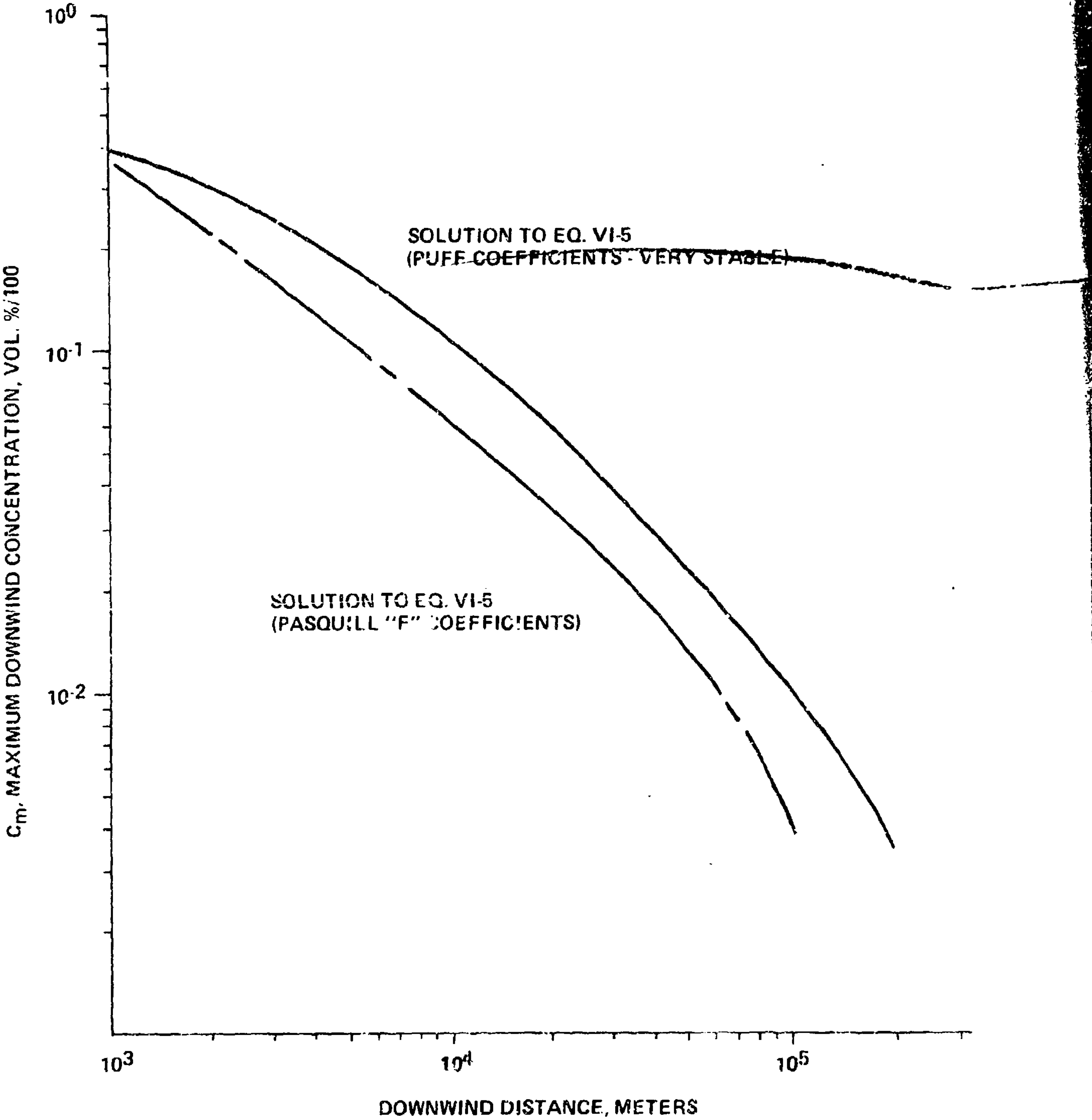


Figure VI-7. COMPARISON OF RESULTS OF FAY'S MODEL USING PUFF COEFFICIENTS AND PLUME COEFFICIENTS

VII. SURVEY OF VAPOR DISPERSION PREDICTIONS ASSUMING STEADY RELEASE OF VAPOR FROM INSTANTANEOUS SPILL OF 25,000 M^3 LNG ONTO WATER-CLASSICAL PLUME MODELS

Burgess (1, 2), Feldbauer (3), and the Federal Power Commission (7) have published predictions for a "worst case," instantaneous, release of 25,000 cubic meters of LNG onto water. All three assume the applicability of the classical steady release or "plume" model for atmospheric dispersion, Equation V-12, restated:

$$C(x,y,z) = \frac{Q'}{\pi \sigma_y \sigma_z \bar{u}} \exp\left[- \frac{1}{2}\left[\frac{y}{\sigma_y}\right]^2 - \frac{1}{2}\left[\frac{z}{\sigma_z}\right]^2 \right] \qquad \text{(VII-1)}$$

Table VII-1 is a summary of the vapor dispersion predictions obtained using the models suggested by Burgess, Feldbauer, and the FPC for a 25,000 cubic meter spill of LNG onto water.

The differences in downwind distances to the 5% concentration level shown in Table VII-1 can be attributed to four factors:

1. The value of Q', the rate of vapor flow into the atmosphere, has been estimated by different methods, with widely varying results. In all cases, however, the predictions reflect the assumption of a steady vapor flow rate from the spill site. (This condition is implicit in Equation VII-1).

TABLE VII - 1
LNG VAPOR DISPERSION PREDICTIONS FOR 25,000 M^3
INSTANTANEOUS SPILL ON WATER BASED ON CLASSICAL PLUME MODELS
(Assumes 5 MPH wind, weather conditions as specified by predicting group)

	BURGESS et al.	FELDBAUER et al.	FEDERAL POWER COMMISSION
1. MAXIMUM LIQUID POOL DIAMETER, FT	1800	2036	1256
2. SPILL EVAPORATION TIME, MIN	11.9	15.0	4.5
3. VAPOR FLOW RATE USED FOR PREDICTION OF DOWNWIND DISTANCE, FT^3/SEC*	7.5×10^5 (1) 2.0×10^6 (2)	6.3×10^5 (3)	1.4×10^5 (4)
4. MAXIMUM DOWNWIND DISTANCE TO 5% (AVERAGE) CONCENTRATION, MILES	25.2 (Q'=750,000ft^3/sec) 50.3 (Q'=2,000,000ft^3/sec)	5.2	0.75
5. MAXIMUM DOWNWIND DISTANCE TO 2 1/2% (AVERAGE) CONCENTRATION, MILES	38.2 (Q'=750,000ft^3/sec) 76.2 (Q'=2,000,000ft^3/sec)	9.5	1.6

* Q' in Equation VII - 1 measured in FT^3/SEC at ambient temperature and pressure

(1) average rate over evaporation period
(2) peak rate during evaporation period
(3) Based on measurements of downwind vapor flow rate from experimental spills, accounts for accumulation of vapor at spill site.
(4) Based on assumption vapor flow rate is limited by heat transfer from atmosphere above pure vapor cloud initially formed.

2. Some groups have included effects due to gravity spreading of the cold LNG vapors; others did not. Where included (FPC, Feldbauer), the modeling processes were dissimilar.

3. The values used for σ_y and σ_z, the horizontal and vertical dispersion coefficients, were not always the same. Different sources of these data have been used and "adjustments" have been made to these data in an effort to more accurately reflect the expected LNG cloud behavior. Finally, the predictions made have not always assumed the same meterological stability conditions, e.g., "neutral" vs. "stable".

4. Modifications have been made to account for the area nature of the source (Equation VII - 1 describes the dispersion from a point source) and the modeling processes were dissimilar.

A description of methods used by each of the four groups to obtain the predictions in Table VII - 1 follows. The calculation of vapor flow rate, allowances for gravity spreading, selection and modification of dispersion coefficients to "fit" LNG behavior, and allowances for the effect of area sources are described in detail. A description of sources of dispersion coefficient data from which all of the groups selected some data is shown in Appendix I.

VII-A. PREDICTIONS USING BURGESS' MODEL (1, 2)

Burgess' model for LNG vapor dispersion is the classical plume model, Equation V - 12, restated:

$$C(x,y,z) = \frac{Q'}{\pi \sigma_y \sigma_z \bar{u}} \exp\left[-\frac{1}{2}\left[\frac{y}{\sigma_y}\right]^2 - \frac{1}{2}\left[\frac{z}{\sigma_z}\right]^2\right] \quad \text{(VII - 2)}$$

where Q' = rate of LNG vapor flow rate downwind

σ_y, σ_z = horizontal and vertical coefficients of dispersion, respectively

$\bar{u}$ = mean wind velocity in the X - direction

Calculation of Vapor Flow Rate

Based on data obtained from approximately steady spills of LNG at rates of the order of one cubic meter per minute, Burgess found the maximum diameter of the LNG pools to be given by

$$D = 6.3 \; W^{1/3} \quad \text{(VII - 3)}$$

where D = maximum pool diameter, feet

W = weight of LNG spilled, lbs

The corresponding evaporation time was found to be

$$T = 2.5 \; W^{1/3} \quad \text{(VII - 4)}$$

where T = evaporation time, sec

W = weight of LNG spilled, lbs

Twenty five thousand cubic meters of LNG weighs 23.4×10^6 lbs. Equations VII - 3 and VII - 4 therefore give a maximum

pool diameter of 1800 feet and an evaporation time of 12 minutes. This corresponds to an average vapor production rate of approximately 750,000 ft^3 per second (at $70^{o}F$, 1 atm). The peak evaporation rate occurs when the pool size is maximum. Burgess used a steady LNG boil off rate of 0.037 lb/ft^2 - sec based on his experimental results. The maximum evaporation rate was then estimated to be about 2,000,000 ft^3 per second (at $70^{o}F$, 1 atm). Burgess then treats the problem as a steady release with 750,000 ft^3/sec and 2,000,000 ft^3/sec as lower and upper limits on the vapor flow rate Q'.

Source of Dispersion Coefficients

Burgess used dispersion coefficient correlations proposed by Singer and Smith (Appendix I). Singer and Smith's correlation of σ_y and σ_z with downwind distance X can be represented by the equations shown below.

ATMOSPHERIC DISPERSION COEFFICIENTS
FROM SINGER AND SMITH (21)
USED IN BURGESS' MODEL

Gustiness Classification (Meteorological Stability)	Plume Dimensions (ft)	
C (Neutral)	$0.42\ X^{0.78}$	$0.29\ X^{0.78}$
D (Stable)	$0.44\ X^{0.71}$	$0.087\ X^{0.71}$

Burgess found that in order to fit his data from small spills using Equation V.1 - 2, the pronounced layering (gravity spreading)

of the vapor which he observed in his experiments had to be accounted for. He found that reasonable agreement between the model predictions and his small scale experimental data was obtained when the correlations for σ_z above were replaced by $0.2\sigma_y$.

Provision for Area Source

Burgess makes no provision for the area source nature of the spill. The predictions are made with Equation VII - 2 which assumes the vapor is released from a point source.

Burgess' predictions of downwind distance to the average 5% concentration level following instantaneous release of 25,000 M^3 LNG in a 5 MPH wind under stable weather (Singer and Smith D category) conditions are shown in Table VII - 1.

VII-B. PREDICTIONS USING FELDBAUER MODEL (3)

Feldbauer (3) has published results of spill tests ranging in size from 250 to 2700 gallons (approximately 1 to 10 cubic meters). Spill times varied from 3 seconds for the smallest spills to 30 seconds for the largest. The basic model used by Feldbauer to describe atmospheric dispersion is the classical plume model, Equation V - 12, restated:

$$C(x,y,z) = \frac{Q'}{\pi\sigma_y\sigma_z\bar{u}} \exp\left[-\frac{1}{2}\left[\frac{y}{\sigma_y}\right]^2 - \frac{1}{2}\left[\frac{z}{\sigma_z}\right]^2\right] \quad \text{(VII - 5)}$$

Calculation of Vapor Flow Rate

Downwind vapor concentrations were monitored by hydrocarbon detectors set in lines at right angles to the wind direction. From concentration vs. time measurements at all locations in a line, and from the wind velocity, the total vapor flow rate past a line of sensors as a function of time was calculated. These data were used to predict the maximum vapor flow rate from the spill area. The maximum vapor flow rate was then used for Q' in Equation VII - 5.

Figure VII - 1 shows Feldbauer's suggested correlation for the maximum LNG vaporization rate from an instantaneous release of LNG onto water. Figure VII - 2 shows Feldbauer's suggested correlation of maximum downwind vapor flow vs. maximum LNG vaporization rate.

For a 25,000 M^3 spill (6,600,000 gal.), from Figure VII - 1, $\dot{\omega}$ = 130,400 lb/sec (3.1×10^6 ft^3/sec at 70°F, 1 atm), and from Figure VII - 2 for a 5 MPH wind, q/W = 0.2. Therefore, the maximum downwind vapor flow rate from a 25,000 M^3 instantaneous spill is estimated to be

$$q = 0.2\ (130{,}400) = 26{,}080 \text{ lb/sec}$$
$$= 6.2 \times 10^5 \text{ ft}^3\text{/sec (at } 70^\circ\text{F, 1 atm)}$$

It should be noted that the rationale for the downwind vapor flow rate being lower than the evaporation rate is the accumulation of dense vapor over the spill site.

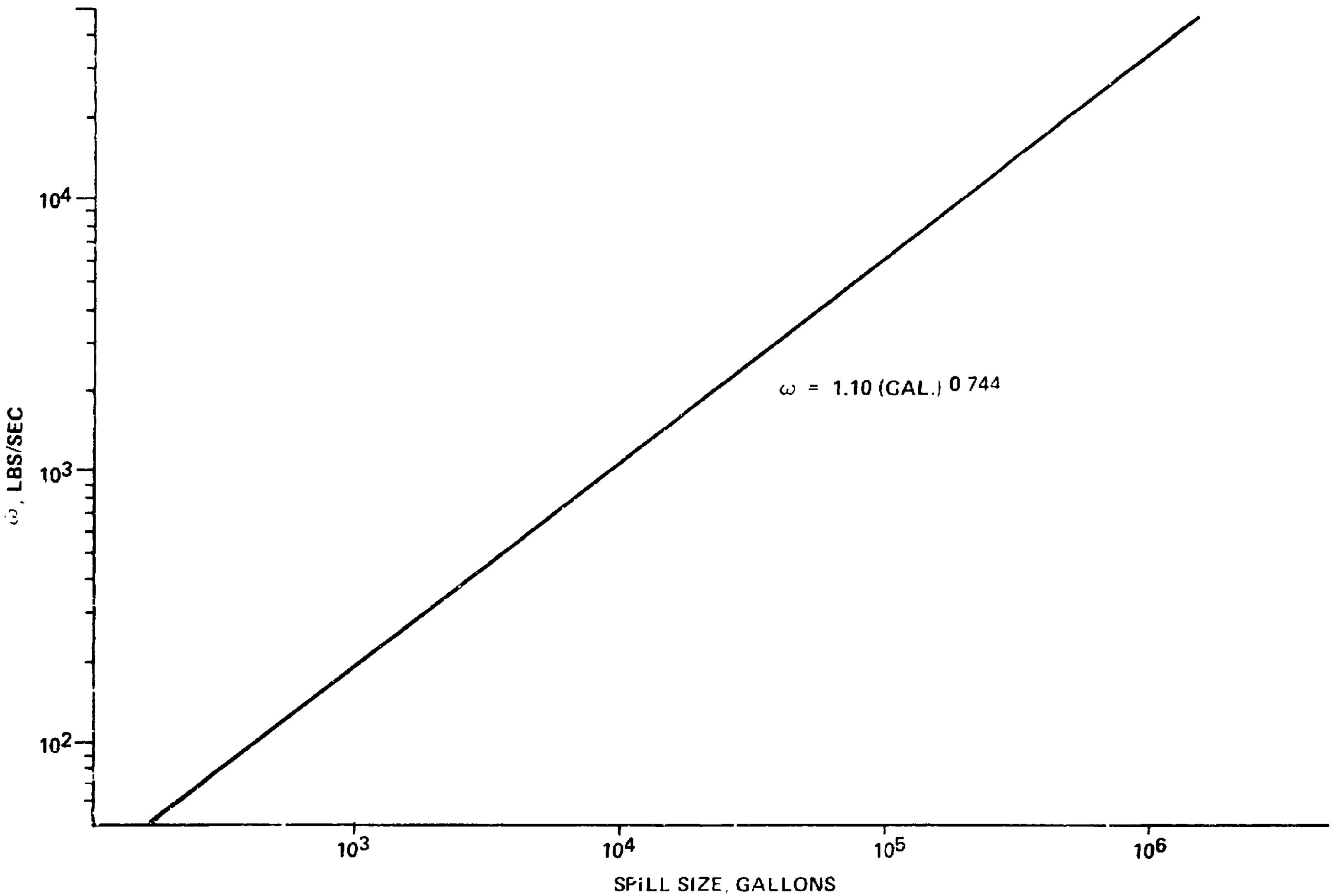


Figure VII-1. MAXIMUM VAPORIZATION RATE $\dot{\omega}$ FOR INSTANTANEOUS SPILLS, FELDBAUER et al. (3)

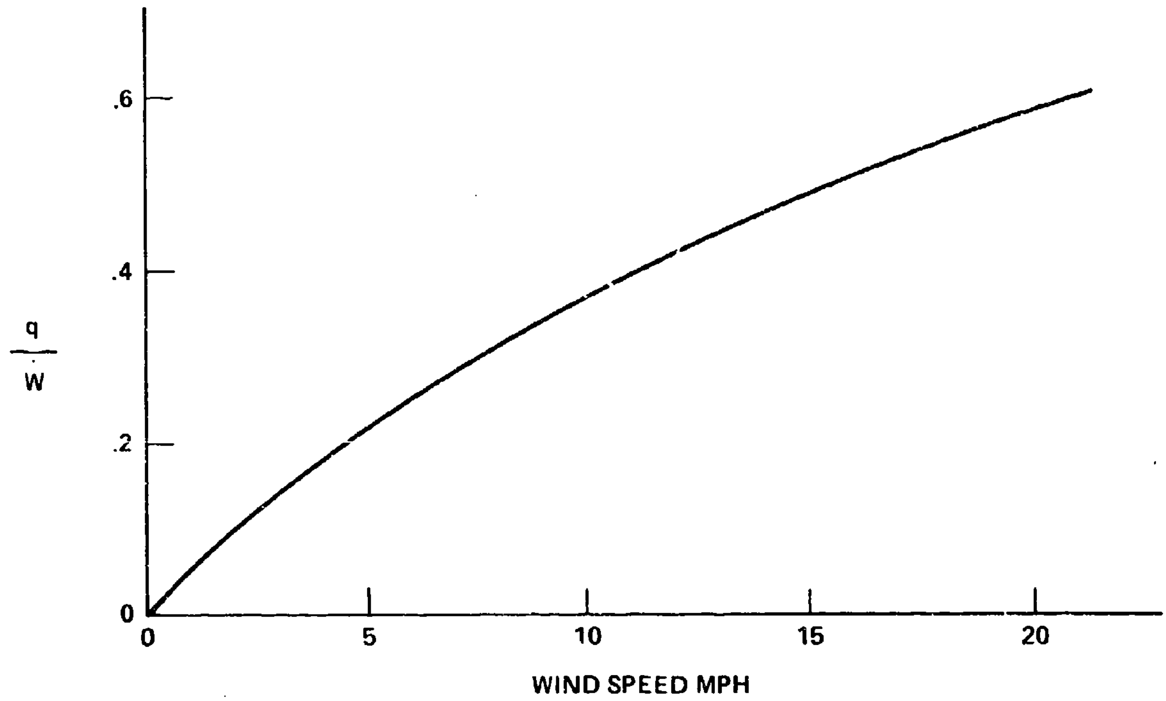


Figure VII-2. EFFECT OF WIND SPEED FOR INSTANTANEOUS SPILLS, FELDBAUER et al. (3)

Allowance For Gravity Spreading Effects

Feldbauer's gravity spread analysis is based on the following equation for the plume width (during gravity spreading) as a function of downwind distance from the spill point suggested by Fannelop and Waldman (41).

$$L = 2.2 \left[\frac{\Delta\rho}{\rho} \; ghLu \right]^{1/3} x^{2/3} \left[\frac{1}{u} \right] \qquad \text{(VII - 6)}$$

where
- L = plume width, ft
- ρ = plume density, lb/ft^3
- $\Delta\rho$ = difference between plume and air densities
- g = gravitational acceleration, ft/sec^2
- h = plume height, ft
- u = plume speed, ft/sec
- x = distance downwind, ft

By taking the derivative of Equation VII - 6 the following equation for the rate of lateral (radial) spread with respect to downwind distance traveled is obtained.

$$\frac{dL}{dx} = 2.2 \left[\frac{\Delta\rho}{\rho} \; gh \right]^{1/3} \left[\frac{1}{u} \right]^{2/3} \left[\frac{L}{x} \right]^{1/3} \qquad \text{(VII - 7)}$$

Equation VII - 7 was used to predict the gravity spread of the cloud as follows.

The spreading plume is assumed to be uniform in concentration and density and approximately rectangular in cross section. At any cross section of the plume the total mass (vapor plus air) flow rate $\dot{M}$ (lbs per second) is given by

$$\dot{M} = \frac{100\ Q'}{C} = hLu\rho \qquad \text{(VII - 8)}$$

where Q' = vapor flow rate, lb/sec

C = vapor concentration, volume %

h = height of plume, ft

L = width of plume, ft

ρ = density of plume, lb/ft^3

u = plume velocity

Solving Equation VII - 8 for L gives

$$L = \frac{100\ Q'}{Chu\rho} \qquad \text{(VII - 9)}$$

In Equation VII - 9 Q' has already been specified. C, h, u, ρ must be determined. A relation between C and ρ is developed assuming adiabatic mixing of air (70°F, 70% relative humidity) with LNG vapor at its boiling point as shown in the first two columns of Table VII - 2. Based on temperature measurements made during the tests, corrections were made to the density to reflect the addition of heat to the cloud due to heat transfer from its surroundings. These

corrections result in the density values given in column 3 of Table VII - 2.

TABLE VII - 2
CALCULATED PLUME DENSITY AS A FUNCTION OF PLUME CONCENTRATION FROM FELDBAUER (3)

Methane Mole%	ADIABATIC $\rho \times 10^3$	CORRECTED* $\rho \times 10^3$
100	115.18	
75	92.76	92.38
50	81.45	81.15
30	75.86	75.43
20	74.28	73.87
0	74.13	74.13

* Corrected for heat transferred to cloud from surroundings using experimental cloud temperature data.

The plume height h is estimated by calculating the amount of vapor accumulation over the spill, assuming its shape to be cylindrical, and solving for h from the relation

$$h = \frac{4V}{\pi D^2} \qquad \text{(VII - 10)}$$

where V = volume of vapor accumulation over spill

D = diameter of spill

Based on correlations derived from their own data, the diameter of a 25,000 M^3 spill was determined to be 2036 feet and the volume of vapor accumulated was calculated to be 2.1×10^8 ft^3 (at LNG boiling temperature and 1 atm). Solving for h from Equation VII - 10 gives h = 66.2 ft. Feldbauer et al. then suggests multiplying this value by 0.6 to account for "diffusion effects". Thus, the initial value of h for a 25,000 M^3 spill is 66.2 x 0.6 = 40 feet. This value of h is assumed to remain constant throughout the gravity spread.

Finally, u, the plume velocity is estimated by assuming a linear relation between vapor weight percent of the cloud and the percent of the wind speed attained. The resulting non-linear relation between volume % vapor and percent of wind speed attained is shown in Figure VII - 3.

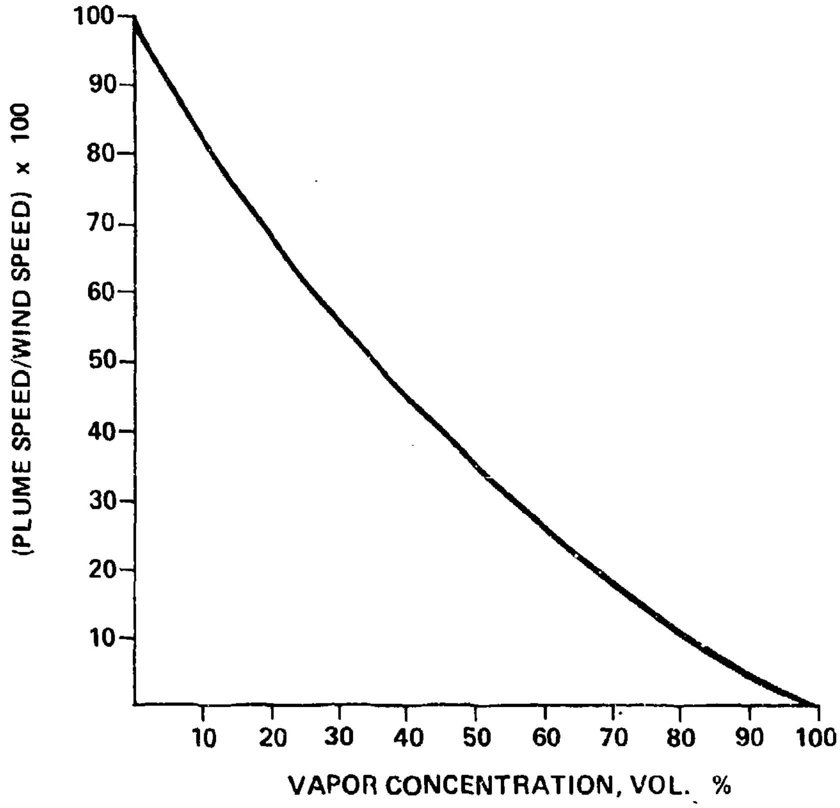


Figure VII-3. PLUME VELOCITY vs. PLUME CONCENTRATION

Equation VII - 9 is then used to calculate the plume width (L) as a function of the vapor concentration, as shown in Table VII - 3. The table is terminated at a vapor concentration of 22.3% since the plume density approaches that of the air at that concentration, i.e., the plume becomes neutrally buoyant at that point and the gravity spread phase of the calculation is terminated.

TABLE VII - 3
PLUME WIDTH VS. CONCENTRATION DURING
GRAVITY SPREAD (FROM EQ. VII-9)

Vapor Concentration, Mole %	Plume Width, Ft.
100	
75	4036
50	4655
40	5793
30	7610
22.3	10,180

Equation VII-7 is then used (Feldbauer multiplied this equation by 2/3 in order "to fit their data") to calculate the relation between plume concentration, plume width, and downwind distance traveled during the gravity spread phase as shown in Table VII-4. The gravity spread calculation was terminated when the plume reached neutral buoyancy, where the plume is predicted to be 10,180 feet wide and 40 feet high.

TABLE VII-4. RESULTS OF INTEGRATION OF EQUATION VII - 7 to DESCRIBE GRAVITY SPREAD OF VAPOR CLOUD FROM 25,000 M^3 LNG SPILL

Methane Mole %	Cloud Width, L, ft	Downwind Distance, X, ft
100		
75	4036	90.3
50	4655	128
40	5793	280
30	7610	596
22.3	10,180	1200

Source of Dispersion Coefficients

Feldbauer suggested the use of the following atmospheric stability classifications for describing the conditions present during their test. Their report implies, but does not explicitly state, that they consider these conditions to be generally representative of stability to be expected over water.

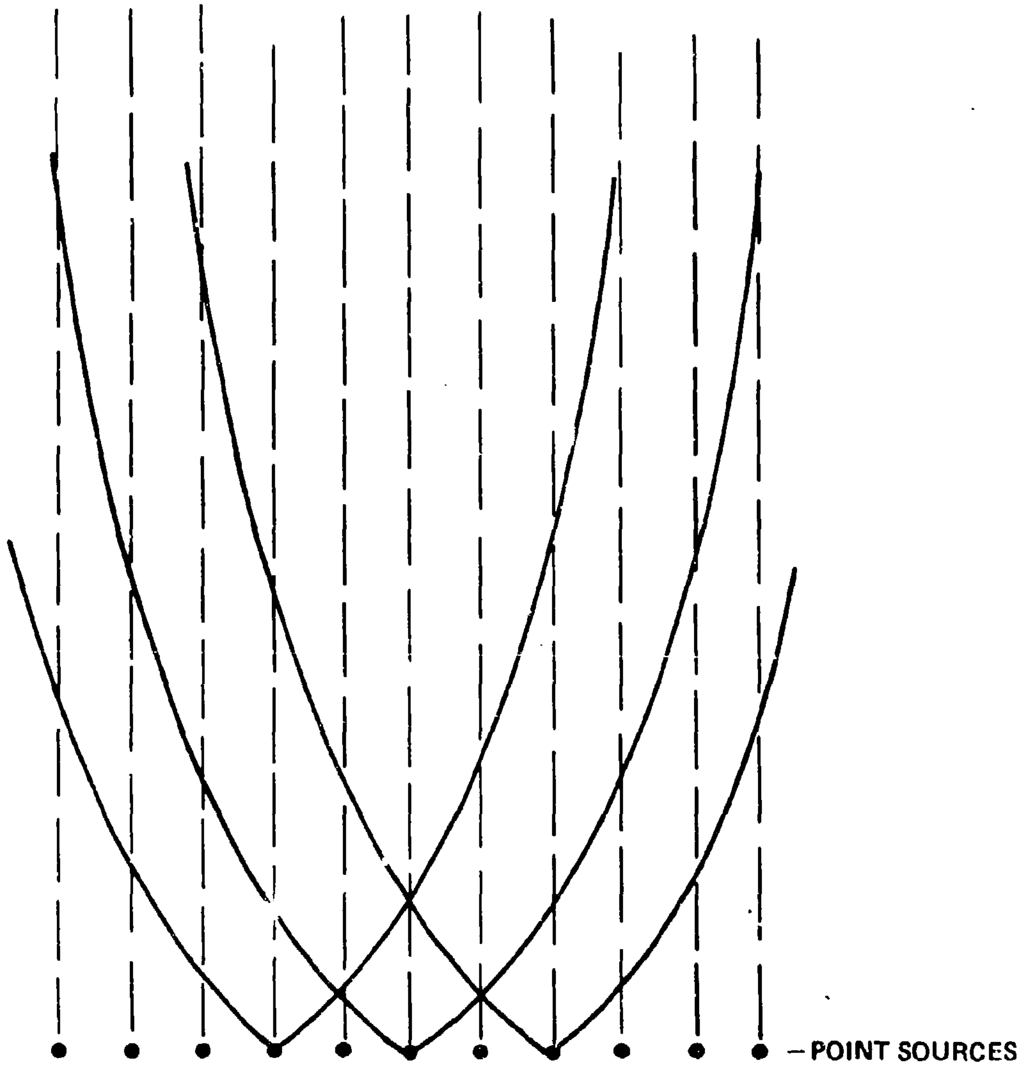
Dispersion Coefficients	Atmospheric-Stability Coefficients
Horizontal Coefficient, σ_Y	Gifford Pasquill - "C"
Vertical Coefficient, σ_Z	Singer and Smith - "D"

The API approach is unique in that all other predictions based on classical plume models to date have utilized the same atmospheric stability category for estimating horizontal and vertical dispersion coefficients (although Burgess did modify the vertical dispersion coefficients to fit his spill data).

Provision for Area Source

Feldbauer's model considers the atmospheric dispersion of the vapor cloud to begin with a cloud [illegible],200 feet wide. They suggest that this "source" for the classical model, Equation VII-5, is too large to be represented by a point source. They assume the source to be represented by a number of point sources spread equidistant along a line equal in length to the width of the cloud resulting from the gravity spread calculation. Following this method, the dispersion in this analysis was assumed to be represented by 11 point sources, separated by equal distances of 1000 feet. Each point source was assumed to emit the total vapor flow rate obtained for the 25,000 M^3 spill (Q' = 26,000 lb/sec or 6.3×10^5 ft^3/sec at 70^oF, 1 atm) divided by 11. A schematic of the arrangement is shown in Figure VII - 4. The downwind concentration is a maximum on the centerline of the center source. This maximum downwind concentration is computed by adding the contribution of all eleven point source plumes to the concentration at the given distance on the centerline of the center plume. The concentration on the centerline of the center plume at any distance downwind is obtained from the equation

$$C(x,y,z=0) = \sum_{1}^{11} \frac{5.73 \times 10^4}{\pi \sigma_y \sigma_z \bar{u}} \exp\left[-\frac{y^2}{2\sigma_y^2}\right] \qquad \text{(VII - 11)}$$



PLUME CONCENTRATIONS ARE ADDITIVE AT ANY POINT. MAXIMUM CONCENTRATION OCCURS ON CENTERLINE OF CENTER PLUME.

Figure VII-4. MULTIPLE POINT (LINE) SOURCE REPRESENTATION OF VAPOR SOURCE FOR 25,000 M^3 INSTANTANEOUS LNG SPILL

where y = 0 for the center plume and

y = 1000, 2000, 3000, 4000, & 5000 feet for the plumes on each side of the center plume

To calculate the distance downwind to the (average) 5% concentration, a distance is assumed, σ_y and σ_z are read from the Pasquill "C" and Singer and Smith "D" dispersion coefficient charts respectively (Appendix I) and Equation VII-11 is solved for C. This process is repeated, by trial and error, until the calculated downwind concentration is 5%. The result for a 25,000 M^3 spill, as shown in Table VII - 1, is 5.2 miles. The downwind distance to the (time average) 2.5% concentration level, calculated using the same procedure, is 9.5 miles.

VII-C. PREDICTIONS USING FPC MODEL (7)

The FPC predictions of LNG vapor dispersion are also based on the classical plume dispersion model, Equation (V - 2) restated:

$$C(x,y,z) = \frac{Q'}{\pi \sigma_y \sigma_z \bar{u}} \exp\left[-\frac{1}{2}\left[\frac{y}{\sigma_y}\right]^2 - \frac{1}{2}\left[\frac{z}{\sigma_z}\right]^2 \right] \quad \text{(VII - 12)}$$

Since the method used by FPC to estimate the vapor flow rate, Q', depends on the extent of gravity spread, it is expedient to describe their handling of the gravity spread process first.

Allowances for Gravity Spread Effects

To calculate the pool size and evaporation time for a 25,000 M^3 instantaneous spill, the FPC staff (7) uses the gravity spread relations proposed by Raj and Kalelkar (15):

EQUATION FOR POOL RADIUS (MAXIMUM)

$$r_e = \frac{7.4\ V_o^{3/8}}{h^{1/4}} \qquad \text{(VII - 13)}$$

EQUATION FOR EVAPORATION TIME

$$t_e = \frac{8.8\ V_o^{1/4}}{h^{1/2}} \qquad \text{(VII - 14)}$$

where r_e = maximum pool radius, ft

t_e = evaporation time, sec

V_o = volume of spill, ft^3 LNG

h = liquid regression rate, in/min

The regression rate is assumed to be one inch per minute, which is equivalent to a vapor flux of 0.037 lb/ft^2- sec or a constant heat transfer rate of approximately 30,000 BTU/hr-ft^2. This is consistent with evaporation rates used by other investigating groups. For V_o = 25,000 M^3 and h = 1 in/min the following values were obtained using Equations VII - 13 and VII - 14.

MAXIMUM POOL DIAMETER = 2511 feet

EVAPORATION TIME = 270 sec (4.5 min)

The LNG vapor from the liquid pool is assumed to "pile up" in a cylindrical volume over the spill. The diameter of the pure vapor cylindrical volume is assumed equal to the maximum

liquid pool diameter. The pure vapor is assumed to be at the LNG boiling point, 112 K, at atmospheric pressure. At this condition the specific volume of the vapor is approximately 250 times that of the liquid. The height of the pure vapor cylinder is calculated from the relation for the volume of a cylinder:

$$h_e = \frac{250\ V_o}{\pi\ r_e^2} \qquad \text{(VII - 15)}$$

where h_e = initial height of pure vapor cloud

V_O = volume of LNG spilled, ft^3

r_e = radius of pure vapor cloud, assumed equal to the maximum liquid pool radius, ft

For a 25,000 M^3 instantaneous spill the height of the pure vapor cloud initially formed is determined from Equation VII - 15 to be 45 feet.

The FPC staff assumes the pure vapor cloud formed over the spill site, as described above, spreads out laterally due to gravitational forces. The spread of this pure cloud, which is assumed to remain pure during the gravity spread process, is calculated using the following equation.

$$\frac{dr}{dt} = \left[Kg \left[\frac{\rho - \rho_A}{\rho_A} \right] H \right]^{1/2} \qquad \text{(VII - 16)}$$

where r = cloud radius, ft

t = time, sec

K = constant, (K = 2 assumed)

g = acceleration of gravity, ft/sec^2

ρ = density of cloud

ρ_A = density of air

(arbitrary, but consistent units)

H = height of cloud, ft

Equation VII - 16 was proposed by Yih (22) as a model for the density intrusion phenomenon, such as the movement of a layer of cold dense air into warmer air (the movement of weather "cold fronts" is an example). It was used later by Fay to describe the spread of oil slicks (23) and LNG (24) on water. It can be derived from physical first principles if it is assumed that the only forces involved in the spread are gravitational and inertial forces, i.e. that surface tension and friction forces are neglected. Substitution of the relation $H = V/\pi r^2$ into Equation VII - 16 and integration with respect to time (assuming V to be constant) gives a relation for cloud radius as a function of time.

$$r = \left[\frac{4Kg}{\pi} \left[\frac{\rho - \rho_A}{\rho} \right] V \right]^{1/4} t^{1/2} \qquad \text{(VII - 17)}$$

However, the total volume of the cloud is assumed to be increasing due to heat transfer from the surroundings. It is assumed that the entire process is to be followed until the cloud density decreases to that of the surrounding air, after which time the gravity spread modeling process is terminated and atmospheric dispersion (associated with atmospheric turbulence) is assumed to dominate. The temperature at which

pure LNG vapor equals the density of air is assumed to be 151 K. Using the ideal gas law it is assumed that

$$\frac{dT}{T} = \frac{dV}{V} \qquad \text{(VII - 18)}$$

during the expansion process. It follows that the final volume of LNG vapor (at 151 K) is related to the initial volume of LNG (at 115 K) by the relation

$$V_N = 337\ V_O$$

where V_N = volume of pure vapor cloud at 151 K (neutrally buoyant)

V_O = volume of pure liquid at 115 K (boiling temperature of LNG)

Assuming that the value for V in Equation VII - 17 can be reasonably represented by

$$\frac{V_O + V_N}{2}$$

and that the cloud density, which is also changing, is represented by the log mean value, the solution of Equation VII - 17 for a 25,000 M^3 instantaneous spill gives the following relation for the radius of the spreading cloud as a function of time.

$$r = 5550\ t \qquad \text{(VII - 19)}$$

where r = radius of cloud, ft

t = time, sec

The spreading process described by Equation VII - 19 is terminated at the time the cloud becomes neutrally buoyant (T = 151 K). The time required for the cloud to reach T = 151 K is estimated by calculating the amount of heat required to raise its temperature from 112 K to 151 K and dividing that amount by the rate of heat transfer to the cloud from the water surface and the air around the cloud.

The heat absorption required to raise the cloud to neutral buoyancy is

$$
\begin{aligned}
q_N &= C_p \, \Delta T \\
&= (0.5 \text{ BTU/lb R}) \, (151 \text{ K} - 112 \text{ K}) \, (1.8 \text{ K/R}) \\
&= 35.1 \text{ BTU/lb} \qquad \text{(VII - 20)}
\end{aligned}
$$

The rate of heat transfer to the cloud is estimated as the sum of the heat transfer rates from the water and the surrounding air, $\dot{Q}_w$ and $\dot{Q}_a$ respectively.

$$
\begin{aligned}
\dot{Q} &= \dot{Q}_w + \dot{Q}_a \\
&= \frac{KA\Delta T_w}{\sqrt{\pi \alpha t}} + hA\Delta T_a \qquad \text{(VII - 21)}
\end{aligned}
$$

where K = thermal conductivity, water (3.13×10^{-4} BTU/meter sec)

A = area, cloud - water interface, $5549 \pi t$

$$\Delta T_w = \Delta T_A = \left[\Delta T_2 - \Delta T_1\right] \Big/ \ln \frac{\Delta T_2}{\Delta T_1}$$

$$\Delta T_2 = 273 - 112 = 161 \text{ K}$$

$$\Delta T_1 = 273 - 151 = 122 \text{ K}$$

α = thermal diffusivity, water (1.42×10^{-7} meter^2/sec)

For a 25,000 M^3 instantaneous spill the total rat of heat transfer, Equation VII - 21, reduces to

$$\dot{Q} = 1.32 \times 10^4 \, t + 2.06 \times 10^5 \, t^{1/2}$$

where $\dot{Q}$ = total heat transfer rate to vapor cloud, BTU/sec (VII - 22)

t = time, sec

The total heat transferred up to the time when neutral buoyancy occurs (t_N) is

$$Q = \int_0^{t_N} \dot{Q}dt = \int_0^{t_N} \left[1.32 \times 10^4 \, t + 2.06 \times 10^5 \, t^{1/2}\right] dt$$

$$= 6.6 \times 10^3 \, t_N + 1.37 \times 10^5 \, t_N^{3/2} \qquad \text{(VII - 23)}$$

$$= 35.1 \text{ W (using Equation VII - 20)}$$

where Q = total heat transferred to cloud, BTU

W = total mass of cloud, lb

Solving Equation VII - 23 for t_N gives a time to neutral buoyancy of 60 sec. From Equation VII - 19 the diameter of the cloud at the time when it becomes neutrally buoyant is then 3785 feet.

Summarizing, the condition of the cloud at the end of the gravity spread process is estimated to be as shown in Table VII - 5.

TABLE VII - 5. VAPOR CLOUD DESCRIPTION AT END OF GRAVITY SPREAD PROCESS - 25,000 M^3 SPILL (FPC)

CLOUD DIAMETER	=	3785 ft
CLOUD HEIGHT	=	28 ft
CLOUD COMPOSITION	=	100% LNG vapor
CLOUD TEMPERATURE	=	151 K

Calculation of Vapor Flow Rate

The FPC's method of calculating the value of the vapor flow rate for use in the classical plume dispersion equation is unique. They assume that the pure vapor cloud which exists at the end of the gravity spread process (see Table VII - 5) will release vapor from its upper surface at a rate determined by the rate at which heat is absorbed by the (now neutral) cloud from the surrounding air. The release rate is calculated from the following relation:

$$Q' = \frac{h\ A}{C} \qquad \text{(VII - 24)}$$

where h = heat transfer coefficient, air to cloud (2.99×10^{-3} BTU/m^2 sec F)

A = area of top surface of neutrally buoyant cloud ($\pi r_N 2 = 1.13 \times 10^7$ ft^2)

C = average sensible heat capacity of cloud (0.5 BTU/lb F)

From Equation VII - 24 the vapor flow rate is calculated to be 6250 lb/sec.

Source of Dispersion Coefficients

The FPC staff estimated dispersion coefficients from the correlations presented by Gifford and Pasquill (see Appendix I). The data presented in the charts of Appendix I have been reduced to analytical equation form and programmed in a computer subroutine by Zimmerman and Thompson (25).

The values of the horizontal and vertical dispersion coefficients are determined from the following equations.

$$\sigma_y = 465.1\ (X + X_v)\ \tan \left[c - [d\ \ln\ (X + X_v)]\right] \qquad \text{(VII - 25)}$$

$$\sigma_z = a\ x^b \qquad \text{(VII - 26)}$$

where σ_y = horizontal dispersion coefficient, meters

σ_z = vertical dispersion coefficient, meters

X = downwind distance, meters

X_v = upwind distance to virtual source, meters

a, b, c, d = constants derived from curve fit of Gifford Pasquill charts (Appendix I)

The values for c and d are functions of stability class only. The values of a and b are functions of distance as well as stability class. Values of a, b, c, d are reproduced from Zimmerman (25) in Tables VII - 6, VII - 7 and VII - 8.

TABLE VII-6. VALUES OF a AND b USED IN EQUATION VII - 26 FOR D STABILITY CLASS

Downwind Distance (km)	a (meters)	b (dimensionless)
0.3-1	32.093	0.81066
1-3	32.093	0.64403
3-10	33.504	0.60486
10-30	36.650	0.56589
>30	44.053	0.51179

TABLE VII - 7. VALUES OF a AND b
FOR USE IN EQUATION VII-26
FOR F STABILITY CLASS

Downwind Distance (km)	a (meters)	b (dimensionless)
0.2-0.7	14.457	0.7841
0.7-1.0	13.953	0.6847
1-2	13.953	0.6323
2-3	14.823	0.5450
3-7	16.187	0.4549
7-15	17.836	0.4151
15-30	22.651	0.3268
30-60	27.074	0.2744
>60	34.219	0.2172

TABLE VII - 8.

VALUES OF c AND d FOR USE IN EQUATION VII-25

Stability Class	c (degrees)	d (degrees)
D - Neutral	8.333	0.72382
F - Stable	4.167	0.36191

It should be noted that the FPC's published predictions of downwind distance to the lower flammable limit (5% average) have been based on the assumptions of D-Neutral stability meteorological conditions.

Allowance for Area Source Effects

The FPC model accounts for the area source nature of an evaporating LNG pool. The area source is treated as a virtual point source located at a distance upwind of the spill which corresponds to a horizontal standard deviation σ_{y_o} given by the relation:

$$\sigma_{y_o} = D'/4.3 \qquad \text{(VII-27)}$$

where σ_{y_o} = standard deviation at spill site equivalent to area source width

D' = width (diameter) of area source at spill site

Equation VII - 27 effectively treats the area source as a cross wind line source with a normal distribution, and was suggested by Holland (26) and Turner (27).

For a 25,000 M^3 instantaneous spill, the FPC estimate for D' is 1154 meters (3790 ft). Equation VII - 27 then gives a value of σ_{y_o} = 268 meters (880 ft). From Equation VII - 25 the virtual distance, X_v, is determined to be X_v = 4.0 km for D-Neutral conditions.

Applying the classical plume dispersion equation (Equation VII - 12) to the centerline condition (y=0), at an effective emission height H,

$$C(x,y=0,z=H) = \frac{Q'}{\pi \sigma_y \sigma_z \bar{u}} \exp\left[-\frac{H^2}{2\sigma_z^2}\right] \qquad \text{(VII-28)}$$

The effective emission height is determined from the relation

$$H = V_{Avg} / \pi r^2_{Avg} = 10.1 \text{ meters} \qquad \text{(VII-29)}$$

where V_{Avg} = time averaged volume of pure cloud during gravity spread, equals 7.39×10^6 M^3

r_{Avg} = (577 + 383)/ 2 = 480 M (average of initial and final gravity spread radii

Substituting values for H and Q' determined above, with u = 5 MPH (2.24 M/sec) into Equation VII - 28 and utilizing the relations for σ_y and σ_z given in Equations VII - 25 and VII - 26 and Tables VII-6, VII-7, and VII-8 for the D stability class, the following relation is obtained:

$$C = \frac{2{,}838{,}000 \quad \exp\left[-\frac{1}{2}\left[\frac{4.0}{32.093\ X^{0.644}}\right]^2\right]}{\pi(465.1)(x+4.0)\tan\left[8.333-(0.7238\ \ln(x+4.0))\right](32.09)X^{0.644}(2.24)} \qquad \text{(VII-30)}$$

where C is in gm/M^3

By trial and error, the solution of Equation VII-30 for X, the downwind distance to the average 5% concentration level (36.6 gm/M^3) following instantaneous release of 25,000 M^3 of LNG during D-Neutral weather conditions, is found to be 1.2 km or 0.75 miles as shown in Table VII-1.

VII-D. COMPARISON OF RESULTS BASED ON STEADY RELEASE MODELS

The downwind distances to the time average 5% concentration level calculated for a 25,000 M^3 instantaneous spill using the

models proposed by Burgess (1,2), Feldbauer (3) and the FPC staff (7) are plotted in Figure VII-5 as a function of vapor release rate used in the predictions. The largest predicted distance, 50 miles, obtained by Burgess using a vapor flow rate equal to his predicted peak evaporation rate is almost 70 times greater than the distance of 0.75 miles predicted by the FPC staff. The downwind distances calculated using Burgess' model with a vapor flow rate equal to his predicted average evaporation rate and with Feldbauer's model lie in between.

Burgess' model does not account for area source effects or effects due to gravity spreading immediately following the spill. Furthermore, his predictions for the "worst case" 25,000 M^3 instantaneous spill assume very stable meteorological conditions. Burgess used Singer and Smith's dispersion coefficients for the D-gustiness category which are a close approximation to the most stable weather category (F) of Pasquill (see Appendix 1). The uppermost line in Figure VII-5, drawn through Burgess' predicted values, therefore, represents a "worst case" downwind distance to the 5% concentration level as predicted by the classical point source steady plume dispersion model. The extreme effect on these predicted distances of the values used for the dispersion coefficients σ_y and σ_z is seen when the same calculations are carried out for weather conditions described by Burgess as B_2-gustiness classification (representative of unstable meteorological conditions). The lower line of Figure VII-5 represents the downwind distance to the 5% concentration

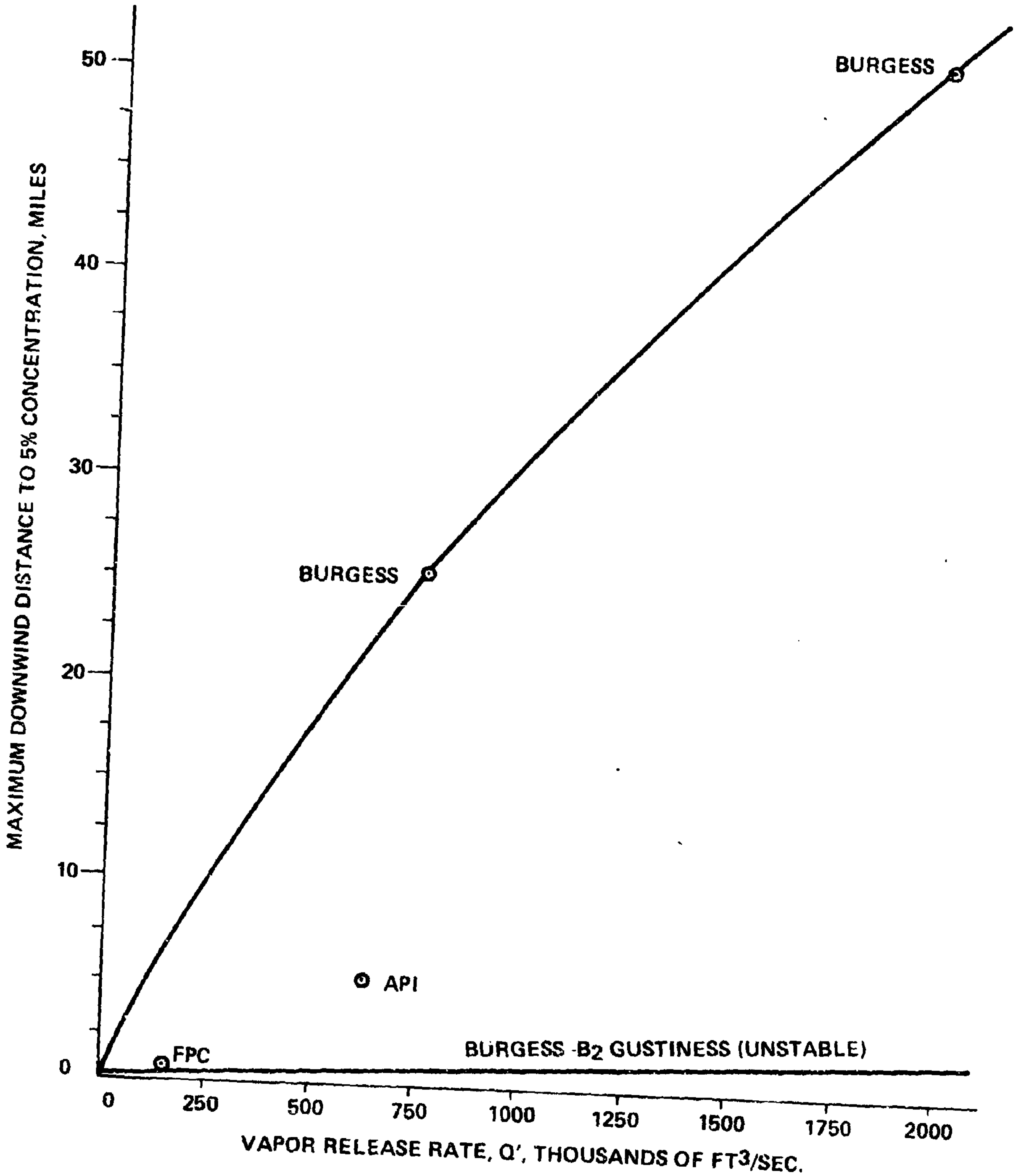


Figure VII-5. COMPARISON OF DOWNWIND DISTANCES TO THE TIME AVERAGE 5% CONCENTRATION LEVEL FOR STEADY RELEASE MODELS

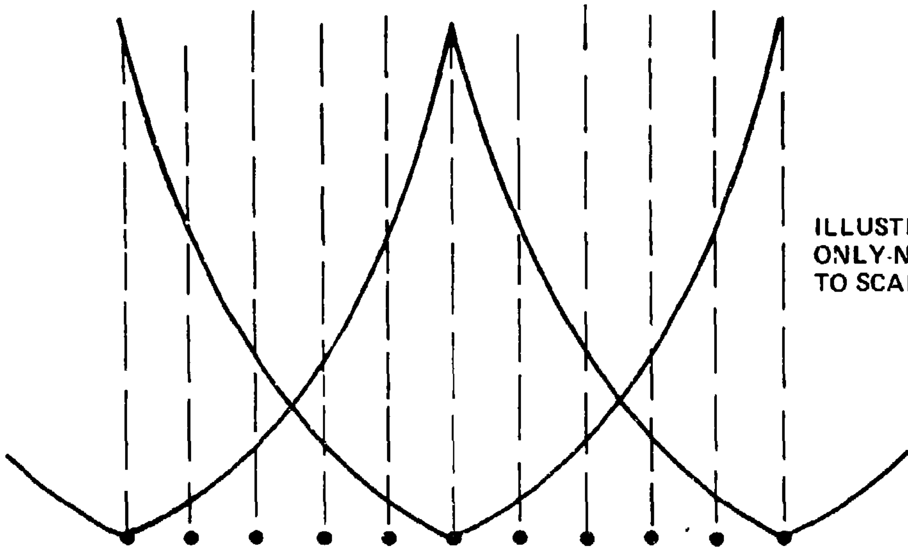
level calculated using the Burgess' model for B_2-gustiness category classification with the values of σ_z set equal to $0.2\sigma_y$ to better describe the vertical dispersion of the dense LNG vapors.

All of the predictions of the downwind distance to the 5% concentration level fall inside these two lines, and the reasons for the different values predicted are indicated by the location of the particular prediction in relation to these two "bounding cases".

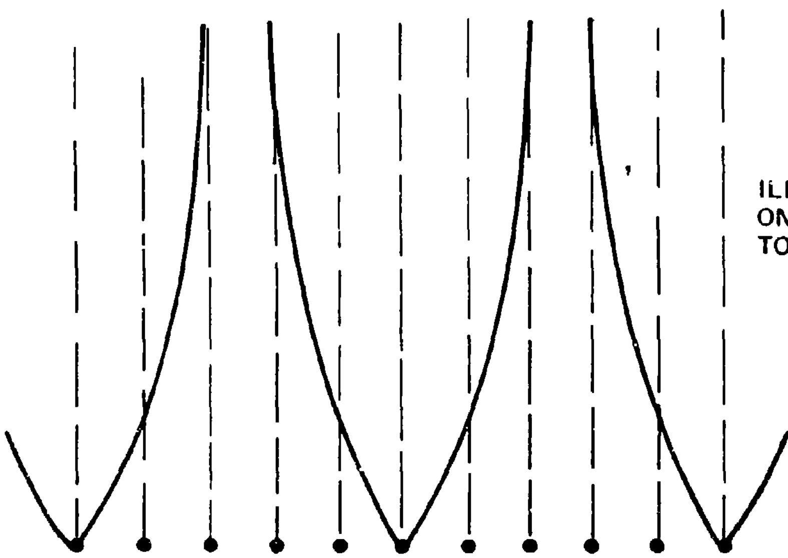
The prediction by Feldbauer of a downwind distance of 5.2 miles can be attributed to two factors. First, the estimate of a much lower vapor flow rate due to the assumption of accumulation of the vaporized LNG over the spill site leads to a shorter distance. Secondly, the treatment of the vapor source as a line source almost 2 miles wide markedly reduces the downwind distance below that whic would be predicted using a point source. Since this line source width results directly from their treatment of the gravity spread phase, the API allowance for gravity spread is a strong factor in the shorter predicted distance. It might be expected that API's use of atmospheric stability category Pasquill - C in the horizontal and Singer and Smith D in the vertical direction would result in a much shorter distance than would have been obtained if the Singer and Smith horizontal stability category D had been used. However, this is not the case. Calculations were made to determine the difference in downwind distance which would be obtained

using the Singer and Smith D stability category for determining the horizontal as well as vertical dispersion coefficients. The distance was calculated to be slightly shorter than 5.2 miles. This surprising result can be explained by referring to Figure VII-6. Figure VII-6-a is a schematic representation of the additive nature of the point sources representing the 10,400 feet line source previously described, using the dispersion coefficients suggested by Feldbauer. Figure VII-6-b is a schematic representation of the additive nature of the point sources representing the 10,400 feet line source, using horizontal (as well as vertical) dispersion coefficients representing Singer and Smith D stability category. Since the horizontal dispersion of the individual point source plumes is reduced, the plumes to either side of the center plume contribute less to the center plume, and the downwind distance along the centerline plume, which is the maximum, is correspondingly reduced. Hence, Feldbauer's predicted distance of 5.2 miles should properly be attributed to the lower vapor production rate and the large gravity spread effect.

The smallest downwind distance to the 5% concentration level, 0.75 miles predicted by the FPC staff, can be attributed primarily to two factors. First, the low value utilized for the vapor flow rate, 143,000 ft^3/sec (70^oF, 1 atm), is the primary reason for the short distance predicted. Secondly, the use of Pasquill D stability category dispersion



A - OFF CENTER PLUMES CONTRIBUTE TO CENTERLINE CONCENTRATION – PASQUILL "C" HORIZONTAL, "F" VERTICAL STABILITY CATEGORY



B - OFF CENTER PLUMES CONTRIBUTE LESS TO CENTER-LINE CONCENTRATION-SINGER AND SMITH "D" STABILITY CATEGORY

Figure VII-6. SCHEMATIC REPRESENTATION OF ADDITIVE PROPERTY OF POINT SOURCES REPRESENTING A LINE SOURCE

coefficients rather than the "worst case" F coefficients also contributes to the shorter distance. The correction for the area nature of the source resulted in a less important reduction in the predicted downwind distance.

VIII. VAPOR DISPERSION PREDICTIONS BASED ON SOLUTION OF COMBINED ENERGY, MOMENTUM, AND MASS BALANCE EQUATIONS - SCIENCE APPLICATIONS, INCORPORATED MODEL

Science Applications, Inc. (SAI) has made predictions of dispersion of LNG vapor from large LNG spills on water in a series of risk assessment studies done for Western LNG Terminal Company (8). SAI's approach involves solution of the system of equations representing the accountability of mass, momentum, and energy associated with an LNG spill. Equations VIII-1, VIII-2, and VIII-3 are balance equations for mass, momentum, and energy respectively, restated as follows:

<u>Accountability of Mass</u>

$$\frac{\partial \rho}{\partial t} = - \nabla \cdot \rho \vec{v} \qquad \text{(VIII-1a)}$$

$$\frac{\partial C}{\partial t} = - \nabla \cdot C \vec{v} \qquad \text{(VIII-1b)}$$

<u>Accountability of Momentum</u>

$$\frac{\partial C \vec{v}}{\partial t} = - \nabla \cdot \rho \vec{v} \vec{v} - \nabla \cdot \overset{\Rightarrow}{\tau} + \rho \vec{g} \qquad \text{(VIII-2)}$$

<u>Accountability of Energy</u>

$$\frac{\partial \rho H}{\partial t} = - \nabla \cdot \rho H \vec{v} - \nabla \cdot \vec{q} + \frac{DP}{Dt} - \overset{\Rightarrow}{\tau} : \nabla \vec{v} \qquad \text{(VIII-3)}$$

where ρ = density of gas-air mixture

H = enthalpy (energy content) of gas-air mixture

$\vec{v}$ = velocity vector, decomposable into components u, v, w

$\vec{q}$ = heat transfer vector, decomposable into components q_x, q_y, q_z

$\overset{\leftrightarrow}{\tau}$ = stress tensor, decomposable into 9 components

$\tau_{xx}, \tau_{xy}, \tau_{xz}, \tau_{yx}, \tau_{yy}, \tau_{yz}, \tau_{zx}, \tau_{zy}, \tau_{zz}$

P = pressure

t = time

$\vec{g}$ = gravity force vector, decomposable into components $g_x = 0$, $g_y = 0$, $g_z = 32.2$ ft/sec^2

$\frac{D}{Dt}$ = substantial derivative operator,

$$\left[\frac{\partial}{\partial t} + \vec{v}\cdot\nabla\right]$$

Solution of Equations VIII- 1, 2, 3 with appropriate boundary conditions describing the LNG vapor source, the air temperature and humidity, and the heat transfer between the gas-air mixture and its surroundings should provide a complete description of the vapor cloud development and dissipation.

The following section describes SAI's simplification of Equations VIII- 1, 2, 3, assignment of boundary conditions, and specification of input data.

Accountability of Mass

Neglecting molecular diffusion in Equation VIII-1b and expanding:

$$\frac{\partial \rho}{\partial t} = -\left[\frac{\partial}{\partial x}\rho u + \frac{\partial}{\partial y}\rho v + \frac{\partial}{\partial z}\rho w\right] \tag{VIII-4a}$$

$$\frac{\partial C}{\partial t} = -\left[u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z}\right] - C\left[\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right] \tag{VIII-4b}$$

Accountability of Momentum

Equation VIII-2 is expanded, with vertical accelerations and viscous forces neglected in the equation for accountability of vertical (Z) momentum:

$$\frac{\partial \rho u}{\partial t} = -\left[\frac{\partial}{\partial x}\rho uu + \frac{\partial}{\partial y}\rho uv + \frac{\partial}{\partial z}\rho uw\right]$$

$$-\left[\frac{\partial}{\partial x}\tau_{xx} + \frac{\partial}{\partial y}\tau_{yx} + \frac{\partial}{\partial z}\tau_{zx}\right] - \frac{\partial P}{\partial x} \tag{VIII-5a}$$

$$\frac{\partial \rho v}{\partial t} = -\left[\frac{\partial}{\partial x}\rho uv + \frac{\partial}{\partial y}\rho vv + \frac{\partial}{\partial z}\rho vw\right]$$

$$-\left[\frac{\partial}{\partial x}\tau_{xy} + \frac{\partial}{\partial y}\tau_{yy} + \frac{\partial}{\partial z}\tau_{zy}\right] - \frac{\partial P}{\partial y} \tag{VIII-5b}$$

$$0 = -\frac{\partial P}{\partial z} + \rho g \qquad \text{(VIII-5c)}$$

Accountability of Energy

The energy balance is simplified by neglecting viscous dissipation (heating due to fluid friction) and heat transfer by conduction (heat transfer due solely to temperature gradients), represented by the terms $\vec{\vec{\tau}}:\nabla\vec{v}$ and $\nabla\cdot\vec{q}$ respectively, in Equation VIII-3.

$$\frac{\partial \rho H}{\partial t} = -\nabla\cdot\rho H\vec{v} + \frac{DP}{Dt} \qquad \text{(VIII-6)}$$

The fluid motion to be described is turbulent. Following standard practice, the variables velocity, enthalpy, concentration, and pressure are expressed as the sum of a mean, or time averaged, component and an instantaneous deviation from that mean value, as follows:

$$\begin{aligned} \vec{v} &= \bar{\vec{v}} + \vec{v}' \\ u &= \bar{u} + u' \\ v &= \bar{v} + v' \\ w &= \bar{w} + w' \\ H &= \bar{H} + H' \\ C &= \bar{C} + C' \\ P &= \bar{P} + P' \end{aligned} \qquad \text{(VIII-7)}$$

Substituting Equation VIII-7 into Equations VIII-4, 5, 6,

taking time averages, and noting that $\bar{\vec{v}}' = \bar{u}' = \bar{v}' = \bar{w}' = \bar{H}' = \bar{C}' = \bar{P}' = 0$,

$$\frac{\partial \rho}{\partial t} = -\left[\frac{\partial}{\partial x}\rho\bar{u} + \frac{\partial}{\partial y}\rho\bar{v} + \frac{\partial}{\partial z}\rho\bar{w}\right] \tag{VIII-8a}$$

$$\frac{\partial \bar{C}}{\partial t} = -\left[\bar{u}\frac{\partial \bar{C}}{\partial x} + \bar{v}\frac{\partial \bar{C}}{\partial y} + \bar{w}\frac{\partial \bar{C}}{\partial z}\right] - \nabla\cdot(C'\vec{v}') \tag{VIII-8b}$$

$$\begin{aligned}\frac{\partial \rho\bar{u}}{\partial t} = & -\left[\frac{\partial}{\partial x}\rho\bar{u}\bar{u} + \frac{\partial}{\partial y}\rho\bar{u}\bar{v} + \frac{\partial}{\partial z}\rho\bar{u}\bar{w}\right] \\ & -\left[\frac{\partial}{\partial x}\rho\overline{u'u'} + \frac{\partial}{\partial y}\rho\overline{u'v'} + \frac{\partial}{\partial z}\rho'\overline{u'w'}\right] \\ & -\left[\frac{\partial}{\partial x}\tau_{xx} + \frac{\partial}{\partial y}\tau_{yx} + \frac{\partial}{\partial z}\tau_{zx}\right]_{\ell} - \frac{\partial P}{\partial x}\end{aligned} \tag{VIII-9a}$$

$$\begin{aligned}\frac{\partial \rho\bar{v}}{\partial t} = & -\left[\frac{\partial}{\partial x}\rho\bar{u}\bar{v} + \frac{\partial}{\partial y}\rho\bar{v}\bar{u} + \frac{\partial}{\partial z}\rho\bar{v}\bar{w}\right] \\ & -\left[\frac{\partial}{\partial x}\rho\overline{v'u'} + \frac{\partial}{\partial y}\rho\overline{v'v'} + \frac{\partial}{\partial z}\rho\overline{v'w'}\right] \\ & -\left[\frac{\partial}{\partial x}\tau_{xy} + \frac{\partial}{\partial y}\tau_{yy} + \frac{\partial}{\partial z}\tau_{zy}\right]_{\ell} - \frac{\partial P}{\partial y}\end{aligned} \tag{VIII-9b}$$

$$0 = -\frac{\partial \bar{P}}{\partial z} + \rho g \qquad \text{(VIII-9c)}$$

$$\frac{\partial \rho \bar{H}}{\partial t} = -\nabla \cdot \rho \bar{H} \bar{\vec{v}} - \nabla \cdot \overline{\rho H' \vec{v}'} + \frac{D\bar{P}}{Dt} \qquad \text{(VIII-10)}$$

where the subscript ℓ in Equations VIII-9a, 9b, denotes "laminar" shear stresses.

The ideal gas equation of state is used to relate density and temperature:

$$\rho = \frac{\bar{P}}{nR\bar{T}} \qquad \text{(VIII-11)}$$

where ρ = density of gas-air mixture

P = pressure

R = ideal gas constant

T = temperature

n = moles of gas mixture, $\left[\frac{1-\bar{C}}{M_a} + \frac{\bar{C}}{M_m}\right]$

M_a = molecular weight of air, 29

M_m = molecular weight of methane, 16

This formulation assumes the pressure is equal to the sum of the partial pressure of air and methane and neglects any contribution by water to the pressure.

The enthalpy of the mixture of water vapor (or ice), methane and air is assumed given by the expression:

$$\bar{H} = \left[C_a(1-\bar{C}) + C_m\bar{C}\right] T + WL_o(1-\bar{C})f(\bar{T}) \qquad \text{(VIII-12)}$$

where C_a = heat capacity of air, 0.24 cal/gm C

C_m = heat capacity of methane, 0.52 cal/gm C

W = mixing ratio of water vapor in air

L_o = latent heat of condensation and freezing of water (675 cal/gm), assumed to occur over a temperature range of -1 C to 1 C

$f(\bar{T})$ = a linear function representing the temperature dependence of the phase transition

The system of Equations VIII-8, 9, 10, 11, 12 cannot be solved without relating the terms involving the velocity, concentration and enthalpy deviations (the primed quantities in Equations VIII-8, 9, 10) to the mean values of those quantities. This is known as the "closure" problem of turbulence modeling. The simplest form of "closure" which has been proposed (the so-called First-Order closure) assumes that the product of the deviation variables are proportional to the gradient of the associated mean values of the same variables. This method is used by SAI in their model for LNG vapor dispersion. Specifically, the following relations are assumed:

$$\rho\overline{u'u'} = K_{x1}\frac{\partial\bar{u}}{\partial x}$$

$$\rho\overline{u'v'} = K_{x2}\frac{\partial\bar{u}}{\partial y} \qquad \text{(VIII-13-a)}$$

$$\rho\overline{u'w'} = K_{x3}\,\frac{\partial\bar{u}}{\partial z} \qquad \text{(VIII-13-a)}$$

$$\rho\overline{v'u'} = K_{x4}\,\frac{\partial\bar{v}}{\partial x}$$

$$\rho\overline{v'v'} = K_{x5}\,\frac{\partial\bar{v}}{\partial y}$$

$$\rho\overline{v'w'} = K_{x6}\,\frac{\partial\bar{v}}{\partial z}$$

$$\overline{\rho H'u'} = \overline{\rho c T'u'} = -\,k_x\,\frac{\partial\bar{T}}{\partial x}$$

$$\overline{\rho H'v'} = \overline{\rho c T'v'} = -\,k_y\,\frac{\partial\bar{T}}{\partial y} \qquad \text{(VIII-13-b)}$$

$$\overline{\rho H'w'} = \overline{\rho c T'w'} = -\,k_z\,\frac{\partial\bar{T}}{\partial z}$$

$$\overline{u'C'} = -\,K'_x\,\frac{\partial\bar{C}}{\partial x} \qquad \text{(VIII-13-c)}$$

$$\overline{v'C'} = -\,K'_y\,\frac{\partial\bar{C}}{\partial y}$$

$$\overline{w'C'} = -\,K'_z\,\frac{\partial\bar{C}}{\partial z}$$

$$\text{and } K_{x1} = K_{x2} = K_{x4} = K_{x5} = K_H \qquad \text{(VIII-14-a)}$$

$$K_{x3} = K_{x6} = K_V$$

$$k_x = k_y = k_H \qquad \text{(VIII-14-b)}$$

$$k_z = k_V$$

$$K'_x = K'_y = K'_H \qquad \text{(VIII-14-c)}$$

$$K'_z = K'_V$$

where K = "eddy viscosity"

k = "eddy thermal conductivity"

K'= "eddy diffusivity"

c = heat capacity

subscript H denotes horizontal

subscript V denotes vertical

Substituting Equations (VIII-13, 14) into Equations (VIII-8, 9, 10) and neglecting laminar shear stresses, the following equations result.

$$\frac{\partial \rho}{\partial t} = -\left[\frac{\partial}{\partial x}\rho\bar{u} + \frac{\partial}{\partial y}\rho\bar{v} + \frac{\partial}{\partial z}\rho\bar{w}\right] \qquad \text{(VIII-15-a)}$$

$$\frac{\partial \bar{C}}{\partial t} = -\left[\bar{u}\frac{\partial \bar{C}}{\partial x} + \bar{v}\frac{\partial \bar{C}}{\partial y} + \bar{w}\frac{\partial \bar{C}}{\partial z}\right] + \left[\frac{\partial}{\partial x}K'_H\frac{\partial \bar{C}}{\partial x} + \frac{\partial}{\partial y}K'_H\frac{\partial \bar{C}}{\partial y} + \frac{\partial}{\partial z}K'_V\frac{\partial \bar{C}}{\partial z}\right] \qquad \text{(VIII-15-b)}$$

$$\frac{\partial \rho \bar{u}}{\partial t} = -\left[\frac{\partial}{\partial x} \rho\bar{u}\bar{u} + \frac{\partial}{\partial y} \rho\bar{u}\bar{v} + \frac{\partial}{\partial z} \rho\bar{u}\bar{w}\right] \tag{VIII-16-a}$$

$$-\left[\frac{\partial}{\partial x} K_H \frac{\partial \bar{u}}{\partial x} + \frac{\partial}{\partial y} K_H \frac{\partial \bar{u}}{\partial y} + \frac{\partial}{\partial z} K_V \frac{\partial \bar{u}}{\partial z}\right] - \frac{\partial \bar{P}}{\partial x}$$

$$\frac{\partial \rho \bar{v}}{\partial t} = -\left[\frac{\partial}{\partial x} \rho\bar{v}\bar{u} + \frac{\partial}{\partial y} \rho\bar{v}\bar{v} + \frac{\partial}{\partial z} \rho\bar{v}\bar{w}\right] \tag{VIII-16-b}$$

$$-\left[\frac{\partial}{\partial x} K_H \frac{\partial \bar{v}}{\partial x} + \frac{\partial}{\partial y} K_H \frac{\partial \bar{v}}{\partial y} + \frac{\partial}{\partial z} K_V \frac{\partial \bar{v}}{\partial z}\right] - \frac{\partial \bar{P}}{\partial y}$$

$$\frac{\partial \bar{P}}{\partial z} = -\rho g \tag{VIII-16-c}$$

$$\frac{\partial \bar{H}}{\partial t} = -\left[\frac{\partial}{\partial x} \rho\bar{H}\bar{u} + \frac{\partial}{\partial y} \rho\bar{H}\bar{v} + \frac{\partial}{\partial z} \rho\bar{H}\bar{w}\right] \tag{VIII-17}$$

$$-\left[\frac{\partial}{\partial x} k_H \frac{\partial \bar{T}}{\partial x} + \frac{\partial}{\partial y} k_H \frac{\partial \bar{T}}{\partial y} + \frac{\partial}{\partial z} k_V \frac{\partial \bar{T}}{\partial z}\right] + \frac{D\bar{P}}{Dt}$$

Equation VIII-17 is further simplified by assuming $\nabla\cdot\vec{v} = 0$ (neglecting compressibility of the gas-air mixture).

Then

$$\nabla\cdot\rho\bar{H}\vec{v} = \vec{v}\cdot\nabla\rho\bar{H} + \rho\bar{H}\nabla\cdot\vec{v} \tag{VIII-18}$$

$$= \vec{v}\cdot\nabla\rho\bar{H}$$

and Equation VIII-17 becomes

$$\frac{\partial \bar{H}}{\partial t} = -\left[\bar{u}\ \frac{\partial \rho \bar{H}}{\partial x} + \bar{v}\ \frac{\partial \rho \bar{H}}{\partial y} + \bar{w}\ \frac{\partial \rho \bar{H}}{\partial z}\right] \qquad \text{(VIII-19)}$$

$$-\left[\frac{\partial}{\partial x}\ k_H\ \frac{\partial \bar{T}}{\partial x} + \frac{\partial}{\partial y}\ k_H\ \frac{\partial \bar{T}}{\partial y} + \frac{\partial}{\partial z}\left[\frac{\partial \bar{T}}{\partial z} + \Gamma\right]\right] + \frac{D\bar{P}}{Dt}$$

where Γ, the adiabatic lapse rate (vertical temperature gradient for a neutrally stable atmosphere), is included to insure that a "neutral" atmosphere is not perturbed by the turbulent diffusion.

Since the hydrostatic approximation (Equation VIII-16-c) provides a relation between the pressure and altitude, it can be used to transform the preceeding equations so that pressure is an independent variable and altitude is a dependent variable. Furthermore, a dimensionless pressure, σ, can be defined as follows:

$$\sigma = \frac{\bar{P}-P_T}{P_S-P_T} = \frac{\bar{P}-P_T}{\pi} \qquad \text{(VIII-20)}$$

where σ = dimensionless pressure

$\bar{P}$ = mean local pressure

P_S = pressure at earth's surface, may depend on position and time

P_T = pressure at upper boundary of atmospheric region being considered

Transformation of Equations VIII-15, 16 and 19 to the x, y, σ, t coordinate systems gives the following system of equations to be solved

$$\frac{\partial \pi}{\partial t} + \frac{\partial}{\partial x}(\pi \bar{u}) + \frac{\partial}{\partial y}(\pi \bar{v}) + \frac{\partial}{\partial \sigma}(\pi \dot{\sigma}) = 0 \tag{VIII-21}$$

$$\frac{D\bar{u}}{Dt} + \frac{\partial \phi}{\partial x} + \frac{\sigma}{\rho}\frac{\partial \pi}{\partial x} = \frac{g^2 \rho}{\pi^2}\frac{\partial}{\partial \sigma}\left[\rho K_V \frac{\partial \bar{u}}{\partial \sigma}\right] + \frac{\partial}{\partial x}\left[K_H \frac{\partial \bar{u}}{\partial x}\right] + \frac{\partial}{\partial y}\left[K_H \frac{\partial \bar{u}}{\partial y}\right] \tag{VIII-22}$$

$$\frac{D\bar{v}}{Dt} + \frac{\partial \phi}{\partial y} + \frac{\sigma}{\rho}\frac{\partial \pi}{\partial y} = \frac{g^2 \rho}{\pi^2}\frac{\partial}{\partial \sigma}\left[\rho K_V \frac{\partial \bar{v}}{\partial \sigma}\right] + \frac{\partial}{\partial x}\left[K_H \frac{\partial \bar{v}}{\partial x}\right] + \frac{\partial}{\partial y}\left[K_H \frac{\partial \bar{v}}{\partial y}\right] \tag{VIII-23}$$

$$\frac{D\bar{H}}{Dt} = \frac{D\bar{P}}{Dt} + \frac{g\rho}{\pi}\frac{\partial}{\partial \sigma}\left[k_V \left[\frac{g\rho}{\pi}\frac{\partial \bar{T}}{\partial \sigma} - \Gamma\right]\right] + \frac{\partial}{\partial x}\left[k_H \frac{\partial \bar{T}}{\partial x}\right] + \frac{\partial}{\partial y}\left[k_H \frac{\partial \bar{T}}{\partial y}\right] \tag{VIII-24}$$

$$\frac{D\bar{C}}{Dt} = \frac{g^2\rho}{\pi^2}\frac{\partial}{\partial\sigma}\left[K'_V\frac{\partial\bar{C}}{\partial\sigma}\right] + \frac{\partial}{\partial x}\left[K'_H\frac{\partial\bar{C}}{\partial x}\right] + \frac{\partial}{\partial y}\left[K'_H\frac{\partial\bar{C}}{\partial y}\right] \quad \text{(VIII-25)}$$

$$\rho = \frac{\sigma\pi + P_T}{\left[\frac{1-\bar{C}}{M_a} + \frac{\bar{C}}{M_m}\right]} \quad \text{(VIII-26)}$$

$$\bar{H} = \left[C_a(1-\bar{C}) + C_m\bar{C}\right]\bar{T} + WL_o(1-\bar{C})f(\bar{T}) \quad \text{(VIII-27)}$$

where $\phi = gz$

and $\frac{D}{Dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + \dot{\sigma}\frac{\partial}{\partial\sigma}$ (substantial derivative operator in x, y, σ, t coordinate system)

The "mathematical" problem of LNG vapor dispersion consists, therefore, of solution of the set of Equations VIII-21 through VIII-27 with appropriate boundary conditions, using finite difference (digital computer) methods. A circular LNG spill shape is assumed. A three dimensional (x, y, σ) grid system is laid out to enclose the volume of the atmosphere into which the LNG is evaporated from the spill. Due to the symmetry of the assumed spill and the resulting symmetry of the dispersion process, only half of the vapor cloud development need to be described. A reflective boundary condition is therefore incorporated at a vertical

plane through the center of the spill coincident with the wind direction. The grid system is illustrated in Figure VIII-1. Figure VIII-1 also illustrates the type of boundary conditions applied to the boundaries of the grid system (28).

As stated previously, SAI assumes that turbulence associated transfers of mass, momentum and energy (heat) are proportional to the local gradients in mean concentration, velocity, and temperature, respectively, in the flow field. An immediate requirement is specification of the eddy transfer coefficients:

K'_H = horizontal "eddy diffusivity"

K'_V = vertical "eddy diffusivity"

K_H = horizontal "eddy viscosity"

K_V = vertical "eddy viscosity"

k_H = horizontal "eddy thermal conductivity"

k_V = vertical "eddy thermal conductivity"

SPECIFICATION OF EDDY TRANSFER COEFFICIENTS

The key process in SAI's specification of the eddy transfer coefficients is the method of specifying the value of the

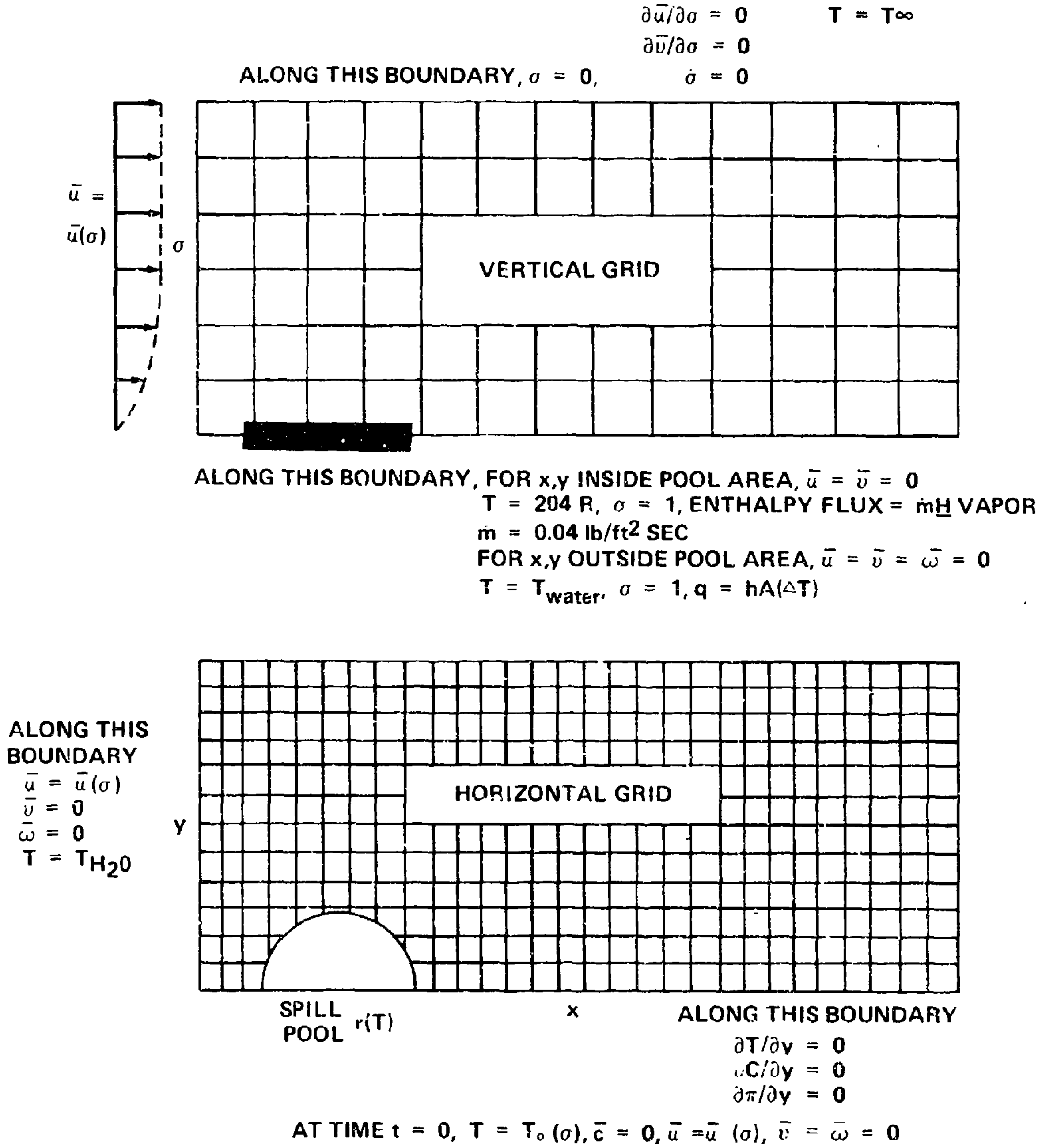


Figure VIII-1. DESCRIPTION OF SAI "SIGMET" GRID SYSTEM AND BOUNDARY CONDITIONS USED FOR LNG VAPOR DISPERSION PREDICTION

vertical "eddy viscosity coefficient", K_V. All of the remaining eddy transfer coefficients are determined from the values assigned to K_V.

The prediction of the vertical eddy viscosity coefficients K_V by SAI is based on a method proposed by Hanna (29). This method assumes that the vertical mixing efficiency of the atmosphere (which is quantified by the value of K_V) is dependent on the mean eddy sizes and the amounts of turbulent energy carried by the eddies. Since the eddy sizes and amounts of turbulent transfer associated with eddy movements are related to the energy spectrum of the vertical fluctuations of the wind speed, it is hypothesized that the eddy viscosity K_V should be dependent on the characteristics of the vertical velocity spectrum of the atmosphere. Hanna assumes that the vertical velocity spectrum can be completely determined by two quantities; the standard deviation of the vertical fluctuations of the wind velocity, σ_w, and the wave number at which the amount of vertical turbulent energy is a maximum, k_m. Based on these arguments, Hanna proposed the following relation.

$$K_V = C_1 \ \sigma_w \ k_m{}^{-1} \tag{VIII-28}$$

For nearly neutral conditions near the ground, Lumley and Panofsky (30) proposed that

$$K = 0.4 \ u_* \ Z \tag{VIII-29}$$

14

$$\sigma_w = 1.3\ u_* \quad \text{(VIII-30)}$$

$$k_m = \frac{0.3}{z} \quad \text{(VIII-31)}$$

where u_* = friction velocity

z = vertical distance

Assuming Equation VII-29, 30, 31 along with Equation VII-28, the constant in Equation VII-28 is 0.09:

$$K_V = 0.09\ \sigma_w\ k_m^{-1} \quad \text{(VIII-32)}$$

Taylor et al. (31) have reported the following correlation between atmospheric turbulence scale length L and k_m derived from spectra of vertical air velocity measured from aircraft at heights between 10 and 1300 meters.

$$L\ k_m = 0.216 \quad \text{(VIII-33)}$$

SAI assumes $L\ k_m = 0.20$. Incorporating this expression into Equation VII-32,

$$\begin{aligned} K_V &= 0.45\ \sigma w\ L \\ &= 0.45\ \bar{u}\ \sigma_\epsilon\ L \end{aligned} \quad \text{(VIII-34)}$$

where $\bar{u}$ = local mean velocity

σ_ϵ = standard deviation of wind direction

Using the data of Taylor et al. (31) SAI proposed the correlation shown in Table VIII-1 to describe the dependence of scale

length on vertical distance, with atmospheric stability category as a parameter.

TABLE VIII-1
CORRELATION OF TURBULENCE SCALE
LENGTH, L, WITH HEIGHT AND ATMOSPHERIC
STABILITY PROPOSED BY SAI

HEIGHT (meters)	STABILITY CATEGORY						
	A	B	C	D	E	F	G
10	18	15	12	10	8	7	6
20	30	25	21	18	16	14	12
30	41	34	29	25	22	20	17
50	62	52	44	39	35	31	27
75	84	71	60	52	48	43	37
100	105	85	74	64	60	54	46

SAI proposed the correlation shown in Table VIII-2 between the standard deviation of the wind direction, σ_ϵ, and vertical distance, with atmospheric stability category as a parameter.

TABLE VIII-2
CORRELATION OF STANDARD DEVIATION OF WIND DIRECTION, σ_ϵ, WITH HEIGHT AND ATMOSPHERIC STABILITY PROPOSED BY SAI

STABILITY CLASS	(10 M)	(30 M and 100 M)
A	0.200 (radians)	0.262 (radians)
B	0.185	0.237
C	0.157	0.184
D	0.117	0.119
E	0.061	0.056
F	0.028	0.023
G	0.012	0.009

The correlation shown in Table VIII-2 was developed by SAI based on data presented in the Shoreline Diffusion Program by Smith and Niemann (32). The vertical eddy viscosity coefficient, K_V, can be specified using Equation VIII-34 and Tables VIII-1 and VIII-2 if the vertical height, atmospheric stability category and local mean velocity are known.

Therefore, SAI assigns a value of K_V, the vertical eddy viscosity, at each grid point of their numerical solution based on the vertical height and local velocity calculated at that point and the atmospheric stability category which is assumed to characterize that location. In order to assign an atmospheric stability category at a given location at a given time, SAI uses the method proposed by Smith and Howard (33) in which the atmospheric stability category is correlated with the vertical temperature gradient.

SAI applies the classical Reynolds analogy to equate the turbulent transfer coefficients for momentum, mass and energy. The components of the vertical eddy viscosity coefficients (see Equation VIII-14a) are also assumed equal.

Hence

$$K_{x3} = K_{x6} = K_V \qquad \text{(VIII-35)}$$

and $$k_z = K'_z = K_V$$

Finally, SAI assumes equality of turbulent transfer coefficients for momentum, mass, and energy in the horizontal plane and assumes the x and y components of these coefficients equal, hence

$$K_{x1} = K_{x2} = K_{x4} = K_{x5} = K_H$$

$$k_x = k_y = k_H$$

$$K'_x = K'_y = K'_H$$

and $$k_H = K'_H = K_H$$

The horizontal transfer coefficients ($k_H = K'_H = K_H$) are then estimated from the ratios of horizontal to vertical transfer coefficients shown in Table VIII-3. Table VIII-3 indicates enhancement of vertical "diffusive" power of the atmosphere relative to horizontal diffusive power when the atmosphere is unstable. The ratios in Table VIII-3 are based on proprietary field data obtained by SAI.

TABLE VIII-3. RATIO OF HORIZONTAL AND VERTICAL DIFFUSIVITIES VERSUS STABILITY CLASS

RATIO	PASQUILL STABILITY CLASS		
	D	E	F
$\frac{K_H}{K_V}$	1.0	10	25

SPECIFICATION OF VAPOR RELEASE RATE

SAI assumed that the liquid pool resulting from an instantaneous release of LNG onto water is circular and increases in size as described by the following equation:

$$\frac{dr}{dt} = \left[2g\left[\frac{\rho_w - \rho_l}{\rho_w}\right] h\right]^{1/2} \qquad \text{(VIII-37)}$$

where r = pool radius, ft

t = time, sec

g = gravitational acceleration, ft/sec^2

ρ_w, ρ_l = densities of water and LNG, respectively, any consistent units

h = pool depth, ft

Equation VIII-37 is used to describe the growth of the spill pool until a minimum pool thickness is reached at which time the pool is assumed to break up. The minimum pool thickness is determined from the relation proposed by Feldbauer et al. (3) based on API sponsored Matagorda Bay test data:

$$Z_{min} = 0.0017\ D^{0.56} \qquad \text{(VIII-38)}$$

where Z_{min} = minimum pool thickness, ft

D = pool diameter, ft

Following pool breakup, the evaporation rate is assumed to decrease according to the following relation also proposed by Feldbauer (3):

$$W = W_{MAX} \exp\left[-\frac{0.04}{\rho Z_{min}}(t-t_{MAX})\right] \qquad \text{(VIII-39)}$$

where W = evaporation rate at time t, lb/sec

W_{MAX} = evaporation rate at time of pool breakup, lb/sec

ρ = LNG density, lb/ft^3

t_{MAX} = time of pool breakup, sec

Equations VIII-37, 38, 39 are used to calculate the pool evaporation rate, assuming a constant boiling rate per unit area of 0.04 lb/ft^2 sec.

Independent calculations by the author of the vapor dispersion following a 25,000 M^3 instantaneous spill were not possible due to the proprietary nature of SAI's computer programs. SAI has not published calculated results for a 25,000 M^3 spill. Therefore, SAI's results for a 37,500 M^3 instantaneous spill are discussed here for comparison with the previous estimates. Table VIII-4 shows SAI's predictions, based on Equations VIII-37, 38, 39, for liquid pool size and evaporation rate for a 37,500 M^3 instantaneous spill onto water. Table VIII-4 shows total vapor production rate as a function of time. In SAI's computer simulation, the evaporating pool is represented as a variable area source by simulation of LNG vapor addition to the atmosphere at the appropriate grid points indicated in Figure VIII-1.

The downwind distance to the time average 5% vapor concentration for a 37,500 cubic meter spill in a 3 m/sec

(6.7 mph) wind calculated using SAI's model (as reported by SAI) is 1.2 miles.

TABLE VIII-4. EVAPORATION RATE AND LIQUID POOL RADIUS PREDICTED BY SAI FOR 37,500 M^3 INSTANTANEOUS LNG SPILL ONTO WATER

Time, sec	Pool Radius, ft	VAPOR PRODUCTION RATE lb/sec	VAPOR PRODUCTION RATE Ft^3/sec at 70F, 1 atm
50	620	4.9×10^4	1.2×10^6
100	869	8.7×10^4	2.1×10^6
150	1050	14.0×10^4	3.3×10^6
200	1184	17.8×10^4	4.2×10^6
250	1184	11.6×10^4	2.8×10^6
300	1184	6.8×10^4	1.6×10^6
350	1184	3.9×10^4	9.3×10^5
450	1184	13.4×10^3	3.2×10^5
520	1184	6.3×10^3	1.5×10^5

IX - ASSESSMENT OF LNG VAPOR DISPERSION PREDICTABILITY FOR CATASTROPHIC SPILLS ONTO WATER

Published predictions of LNG vapor cloud formation and dispersion following a catastrophic spill of LNG on water can be categorized as follows:

1. Predictions which utilize classical air pollutant dispersion models originally developed to describe relatively near-field dispersion of neutrally buoyant materials. These models are based on the general observation that the concentration profiles downwind of a pollutant source are reasonably accurately represented by a Gaussian or normal distribution. This model type is further subdivided to describe two different dispersion phenomena:

a. Dispersion of an essentially instantaneous release of a given amount of pollutant into the atmosphere, the dispersion being associated with the growth of this instantaneously released "puff", or cloud, as it is being translated by the wind.

b. Dispersion of material which is being emitted at a continuous, steady rate forming a "plume" downwind of the emission source.

2. Predictions based on solution of the combined mass, momentum and energy balance equations. The classical air pollutant dispersion equations of category 1 above are a

special case where energy effects and momentum effects are not explicitly considered. In cases where the material added to the atmosphere has a substantially different temperature and density than that of the atmosphere consideration of energy and momentum effects can be important.

Comparison of published predictions of the downwind travel of flammable gas-air mixtures following the instantaneous release of 25,000 cubic meters of LNG onto water identifies the sensitivity of such predictions to the following factors.

a. Characterization of atmospheric stability

b. Allowances for area source effects

c. Specification of vapor release rate

d. Allowances for gravity spread/air entrainment effects

The choice of atmospheric stability category assumed applicable to the accident scenario strongly affects the downwind distances predicted using models based on the classical pollutant dispersion equations. The use of stability characterizations other than those representing "inversion" or very stable conditions for "worst case" evaluation is difficult to justify, in the author's opinion, since the latter may occur frequently.

Allowances for area source effects incorporated with the classical pollutant dispersion equation models rely on specification of a point "virtual" source (CHRIS, Germeles and Drake, FPC), or line source representation (Feldbauer), for the predictions shown herein. Incorporation of these techniques affects the predicted distances more for unstable

weather conditions than for stable conditions, since the correction for the initial spreading effect is a smaller percentage of the total distance in the latter case.

This review shows that much of the variation in predicted downwind distances is due to differences in estimation of the rate of vapor flow into the atmosphere. For example, the shortest distance predicted for an instantaneous 25,000 cubic meter spill is 0.75 miles by the FPC staff. This short distance can be viewed as resulting primarily from the low estimated rate of vapor flow into the atmosphere and to a lesser but still important degree from the use of neutral weather stability dispersion coefficients. It should be noted that the FPC model predicts an evaporation time of only 4.5 minutes for a 25,000 M^3 instantaneous spill which corresponds to an average vapor production rate approximately the same as predicted by the ADL - CHRIS model. However, the FPC staff assumes that this vapor "piles up" above the liquid pool in pure form and only begins to enter the atmosphere after the cloud becomes neutrally buoyant (i.e. when its density reaches that of the air), during which time it spreads as a pure cloud to a diameter of 3,785 feet. The FPC then assumes the rate of vapor "release" from this pure cloud to the atmosphere is limited by the rate of heat transfer from the surrounding air to the cloud's upper surface. This assumption results in a vapor release rate of 6,250 lb/sec, which indicates the

cloud would release vapor from its top surface at this steady rate for almost 18 minutes. There appears to be no technical justification for this description of the vapor flow rate and it is considered by the author to be unacceptably low. Furthermore, as long as the classical air pollutant dispersion models are used, there does not appear to be any valid reason why the worst case atmospheric stability conditions should not be used to predict the maximum downwind distance. For these reasons, the short distance predicted by the FPC staff cannot be accepted based on their technical arguments.

LNG vapor, when it is initially formed at the boiling pool surface, is at a temperature of about -260°F and the vapors at this temperature are almost 1 1/2 times as heavy as air. When large quantities of this dense vapor are rapidly released into the atmosphere the cloud formed should tend to remain close to the water surface, i.e., its vertical dispersion should be suppressed. The experimental spills which have been made on water to date (1, 2, 3, 10) confirm this behavior. Fay (6), Germeles and Drake (4), Burgess (1, 2), Feldbauer (3) and the FPC (7) have all attempted to modify or augment the classical pollutant dispersion models to account for this effect. However, the methods used for this purpose by these groups are not similar, and the predicted effect on dispersion directly attributable to gravity spread action varies from slight

(Fay, Burgess, FPC) to very large (Feldbauer). The results obtained from the Germeles and Drake model are sensitive to the numerical values of the parameters which relate to the gravity spread phase and its associated air entrainment. An important pattern can be recognized in the techniques surveyed that are based on classical air pollution dispersion models. Where gravity spread has been considered along with air entrainment by the advancing gravity spreading cloud, results show that inclusion of both effects can markedly reduce the prediction of downwind travel to the lower flammable limit for very large, rapid spills. Variation of the air entrainment parameter in Germeles and Drake's model by a factor of 5 results in prediction of the average cloud concentration dropping below the lower flammable limit during the gravity spread phase of a 25,000 M^3 instantaneous spill. Although variation of the air entrainment parameter by a factor of 5 upward (and 10 downward) may not represent a physically realizable range, it does show the sensitivity of the resulting prediction to the numerical quantification of the air entrainment. In view of the suggested sensitivity of the result to the degree of air entrainment by the spreading cloud, the importance of correctly modeling the dispersion of the cloud associated with gravity spreading of the dense cloud is apparent.

If gravity spreading induced effects are not considered to be important, classical models suggest that substantial downwind travel of the cloud will occur before the concentration

decreases to the non-flammable range. Furthermore, the predicted downwind distance to the lower flammable limit following very large spills of LNG appears to depend strongly on the degree of dispersion attributed to the initial gravity spread phase.

In the author's opinion future attention should be centered on the development and verification of models which include some explicit procedure for describing the early development of the cloud, including a method for quantifying the air entrainment which may be associated with gravity spread induced turbulence. The Germeles and Drake model and the SAI model both address this need; Burgess' model, Fay's model, the FPC model and the CHRIS model do not. The model suggested by Feldbauer provides for mixing of air and vapor during gravity spread by assuming the cloud depth to remain constant during the spreading process. This approach appears to be based on the experimental observations of Feldbauer, and the validity of extension to very large spills is uncertain.

It is also the opinion of the author that any model to be used for predicting the dispersion of vapor from very large spills should take into account energy effects associated with mixing LNG vapor and air. Furthermore, since the most important question concerning the validity of previously used models concerns the degree of dispersion which may result due to the action of the cloud itself (i.e. by gravity spreading and associated air entrainment), future attention should be centered on development of

models which are capable of accounting for simultaneous effects of energy transfer, gravity induced spreading, and turbulent diffusion. The Germeles and Drake model accounts for gravity spread effects, energy effects associated with mixing LNG vapor and air, and air entrainment, utilizing a lumped parameter approach which assumes the developing cloud to be spatially uniform (but changing with time) during the gravity spread phase. The Germeles and Drake model provides a framework for inclusion of important physical effects, even if in a simplified form. The SAI model accounts for gravity spread, energy effects associated with mixing LNG vapor and air, and air entrainment by solving a less simplified form of the mass, energy and momentum balances. In this regard, the SAI technique provides several advantages as follows:

1. The technique allows for a representative description of the true transient nature of the spill phenomena. For example, the rate of vapor production from the spill can be represented in a much more realistic time varying form.

2. Inclusion of the energy balance equations allows description of the temperature development of the cloud in a more realistic way. In the SAI method, the temperatures and concentrations in the cloud are considered to be functions of both time and location, whereas even the most sophisticated previous models (Germeles and Drake) assume the cloud temperature and concentration during the initial phase of development to be uniform while varying with time.

3. Phenomenological relationships, particularly the

coefficients of turbulent diffusion, can be specified as a function of both time and position. This is significant since the turbulent diffusion properties of the cloud would be expected to vary in both time and space due to the progressive mixing of the cold vapor with air. The simpler classical models assume implicity that the turbulent diffusion of the vapors occurs without affecting the pre-existing turbulence patterns in the atmosphere.

The primary reason for the much shorter downwind distances to the 5% concentration level predicted by SAI for a catastrophic spill appears to be the predicted highly turbulent motion associated with the gravity spread phase. This high degree of predicted turbulence at the spreading cloud-air interface is responsible for significant air entrainment by the cloud. Since the predicted turbulence is primarily induced by the spreading action of the cloud, this provides an explanation for why the turbulence properties assigned to the surrounding atmosphere at the time of the spill (i.e. neutral vs. stable) do not markedly affect SAI's predicted results. The results of the model predictions indicate that the principal dispersion of the vapor to the point where the concentration is below 5% is associated with effects caused by the cloud spread itself, rather than the prevailing atmospheric conditions. It is interesting to note that the gravity spread analyses proposed by Germeles and Drake (4) and Feldbauer (3) lend support to this idea.

However, it is also the author's opinion that certain questions must be answered concerning the predictions of the SAI model before the results cited herein can be confidently accepted. The specification of the turbulent diffusion coefficients, e.g., the "eddy viscosity" coefficient, must be more carefully evaluated. As has been described in Section VIII, the local specification of these transfer coefficients is a rather complex process involving several assumptions. The assumption of equality of coefficients representing mass, momentum, and energy transfer requires careful scrutiny. It should be noted that Hanna (29), whose work provides the basis for SAI's estimation of turbulent diffusion coefficients, did not generally support this assumption for determination of the coefficient of energy transport. Smith and Niemann (32) have raised questions about the general validity of the basic relationships between the energy spectrum and the wind speed and direction variation assumed by Hanna (20) and used by SAI. Furthermore, it is difficult to assess the uncertainty in the ultimate specification of the coefficients introduced by the relations proposed by Taylor (31) for turbulence scale length. For example, the data of Taylor et al., on which Equation VIII-33 is based, is very scattered. Pasquill (12) has questioned the validity of such precise correlations of the turbulence scale length with energy spectrum parameters. Finally, the method used by SAI still involves the requirement to assign, locally, stability categories of the classical

type (e.g., Pasquill A-F) to the developing cloud. The method used is based on the work of Smith and Howard (33) and considers the stability category to be a function of the local temperature gradient. This correlation is based on measurements of atmospheric turbulence under relatively stationary (in the statistical sense) conditions and the assumption that the same correlation applies in a methane rich cloud which is in a highly nonstationary state is not obvious. It must be emphasized that the advantages which obtain from the use of a complex model such as that proposed by SAI can be easily vitiated by the incorporation of techniques for descriptions of turbulence which are not easily verified. Until further studies validate this part of the overall approach, we may only be trading uncertainty in the classical models for a new, but no less important, uncertainty in more complex models.

There remains the problem of verification of the numerical procedures used in the computer solution of the SAI model. This study did not address the need for a thorough, independent, evaluation of the computer program to verify the numerical accuracy and stability of the solution technique.

There are other techniques which might be applied to the vapor dispersion problem. The obvious one which might be suggested is to use a turbulence "closure" model of higher order. These methods are proposed when the assumption of proportionality between the mean gradients of concentration,

velocity, and temperature and their respective turbulent transfers is not considered applicable. A large body of literature has developed in this area (34, 35, 36) but this study has not addressed it in detail. However, until the basic questions posed above concerning the SAI model are answered, there is little justification for pursuing a more sophisticated model. The adage that more complexity does not insure more validity applies directly to this problem.

There are other important questions related to the predictability of vapor dispersion from catastrophic spills of LNG on water which have not been addressed in this report. All of the predictions of downwind distance which have been surveyed in this report have been compared at the time average 5% concentration level. For comparison, the downwind distance to lower time average concentrations has been shown for some of the models. There is still disagreement as to the magnitude of the peak-to-average concentration ratios that would characterize a vapor cloud resulting from a catastrophic spill and this affects the choice of time average concentration which limits the flammable region of the cloud. In the author's opinion, this uncertainty does not affect the comparative assessment of the models discussed in this report. Unless a model can be developed which provides accurate time average concentrations, the accurate <u>prediction</u> of peak-to-average concentration rates effects cannot be anticipated.

An additional facet of LNG vapor cloud dispersion which is important to the assessment of potential hazard is the <u>width</u>

of the flammable zone. Analysis of the models surveyed in this report indicates a marked variation in the width of potentially hazardous zones. Since the area exposed to potential ignition sources and/or the burning cloud determine the exposure to such an accident, an accurate estimate of the shape of the cloud is required. However, the author believes that the comparison of the models described in this report based only on predicted downwind extent of the flammable zone is sufficient to justify the assessment made and the recommendations for further evaluation which are offered.

It is important to re-emphasize that this report is intended to deal only with the predictability of catastrophic LNG spills on water. The conclusions to be drawn are not necessarily appropriate for the consideration of the predictability of vapor dispersion from small LNG spills on water or land. For small spills, the allowance for heat transfer effects and momentum transfer effects in the prediction of the dispersion appears much less important. Experimental evidence from LNG spills on the order of 10 cubic meters and smaller support this contention. Figure IX-1 is a comparison of downwind, ground-level concentrations predicted using Burgess' model and the SAI model, as described in this report, with experimental data from an American Gas Association experimental program (33). The spill described was a rapid release of 14,000 gallons of LNG on land. The spill was confined by an 80 feet diameter, 1.5 feet high dike. Maximum vapor production

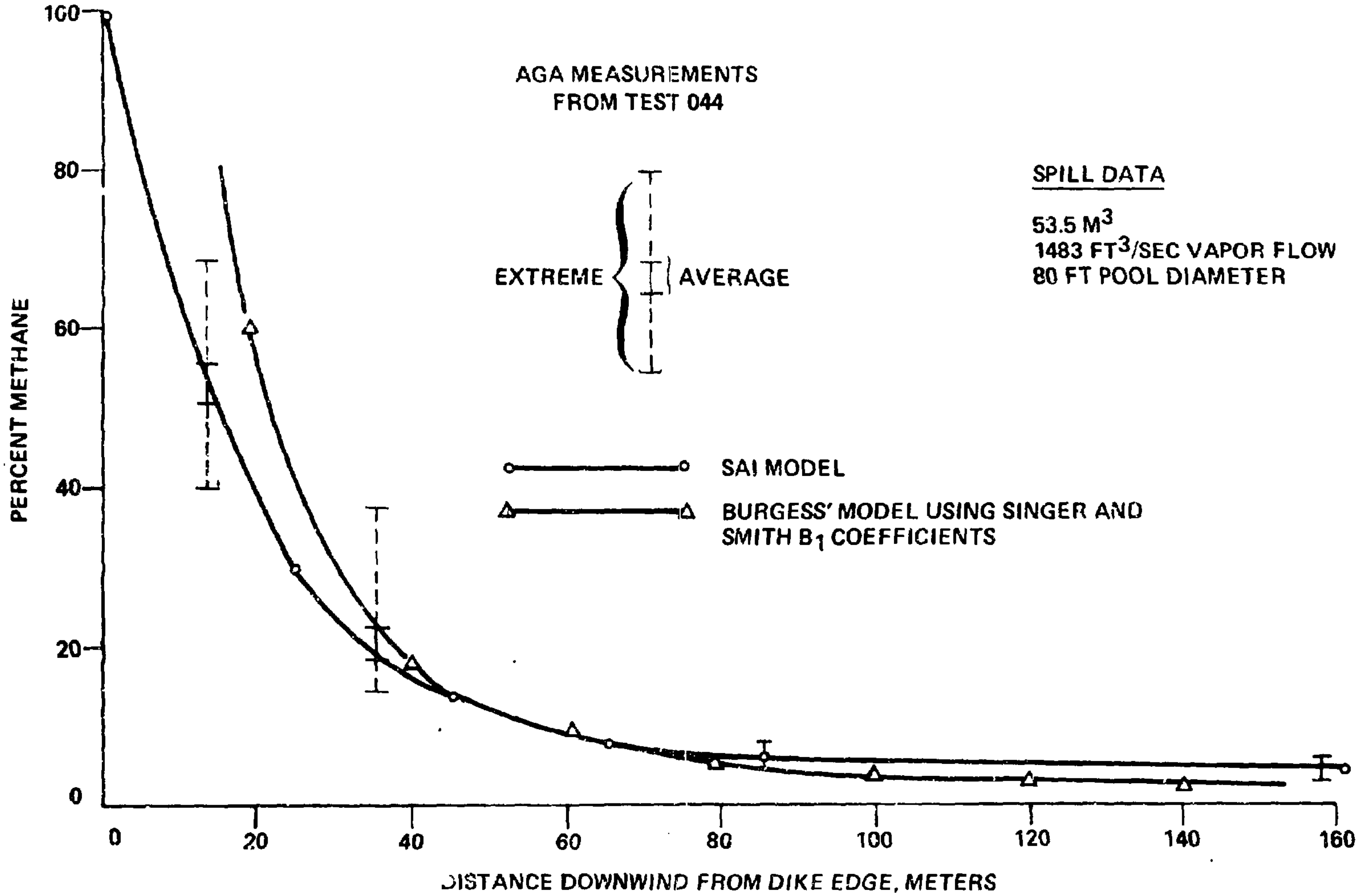


Figure IX-I. COMPARISON OF GROUND LEVEL CONCENTRATIONS FROM AGA TEST 044 WITH PREDICTIONS BY SAI MODEL AND BURGESS' MODEL

rates were measured in the experiments and reported as 0.09 cubic meters per second at $-260^{o}F$ (0.72 inches LNG per minute). The atmospheric stability conditions reported for the experiment (AGA 044 in the test series) were reported as Pasquill "C", with a wind velocity of 12 miles per hour. The vertical hash marks represent the range of concentrations measured at downwind positions. The solid predicted curve is taken from SAI's published risk assessment study for Oxnard, California (8). The dashed line was calculated by the author using Burgess' model with Singer and Smith B_1 stability coefficients. Following Burgess, the vertical dispersion coefficient σ_z was equated to $0.2\sigma_y$ and the vapor source was assumed concentrated at the pool center. The maximum experimentally measured vapor production rate was used in both models.

Note that the downwind distance to the 5% level is essentially the same for both models. This is in contrast to the difference in downwind distances to the 5% concentration predicted using these models for a 25,000 cubic meter spill as shown in Table IV-1 of this report. Two things are immediately apparent from this comparison. First, sufficient accuracy may be obtainable from both classical dispersion models and the SAI model for the prediction of LNG vapor dispersion from small spills on land or water. Second, experimental data from small spills validates several models for prediction of that type of phenomena, while shedding no light on the question of validity of the models for predicting vapor dispersion from very large spills.

X. CONCLUSIONS

1. This review and comparison of published predictions of the downwind travel of flammable gas-air mixtures following the instantaneous release of 25,000 cubic meters of LNG onto water identifies the sensitivity of such predictions to the following factors.

   a. Characterization of atmospheric turbulence (stability)

   b. Allowances for area-source effects

   c. Specification of vapor release rate

   d. Allowances for gravity spread/air entrainment effects

2. The shortest distance to the time average 5% concentration level for a 25,000 cubic meter instantaneous spill predicted by the models reviewed herein is 0.75 miles. This distance, predicted by the FPC model, results primarily from the use of an unrealistically low vapor release rate and the use of neutral atmosphere stability characteristics. The FPC estimate, in the author's opinion, is not justified.

3. At the other extreme, distances of the order of tens of miles are predicted for a 25,000 cubic meter instantaneous spill under stable weather conditions using continuous plume models (Burgess) which do not account for any heat transfer

cr momentum transfer effects. Such estimates are not justified in this author's opinion.

4. Intermediate distances to the 5% concentration level are predicted for a 25,000 cubic meter spill during stable weather conditions by Germeles and Drake (11.5 miles), Fay (17.4 miles) and the CHRIS model (16.3 miles). The difference in predicted downwind distances obtained with the CHRIS and Germeles-Drake models can be attributed primarily to the inclusion of gravity spread/air entrainment effects in the Germeles and Drake Model. The rough agreement of these two predictions with the value of 17.4 miles predicted by Fay must be considered fortuitous since the modeling process assumed by Fay is quite different from the other two. Professor Fay now believes (42) that his model should be used with different assumptions than originally described by Lewis and Fay, in which case substantially longer distances result. In the author's opinion the model of Germeles and Drake provides a more plausible estimate of the LNG dispersion process following a large rapid spill than the Fay or CHRIS models, since the model incorporates a rational, if simplified, description of an anticipated gravity spread phase. Further effort to improve this type model as an alternative to a more complex numerical procedure has merit, particularly for routine usage where time and expense constraints are important.

5. The estimate using Feldbauer's model of 5.2 miles for the downwind distance to the 5% concentration level following a 25,000 cubic meter spill can be attributed to the predicted dilution and corresponding extreme width (~2 miles) of the cloud at the end of the gravity spread phase. Feldbauer's allowance for air entrainment during the gravity spread, which involves the assumption of constant cloud depth, is based on observations of small spills (10 M^3) and the extension to very large spills appears uncertain. Further, representation of the cloud at the end of the gravity spread phase as a series of dispersed point sources on a line perpendicular to the direction of cloud travel is not realistic in view of the resulting prediction of shorter distances with increasing atmospheric stability.

6. The primary reason for the even shorter downwind distance (~1 mile) to the 5% concentration level predicted by SAI for an even larger (37,500 cubic meters) spill appears to be the predicted highly turbulent motion and associated air entrainment induced during the gravity spread phase of the cloud.

7. In the author's opinion, the predicted maximum distances of about 5 miles by Feldbauer and about 1 mile by SAI for flammable cloud travel following instantaneous release of 25,000 cubic meters of LNG onto water cannot be rationalized on the basis of any argument thus far advanced except that of gravity spread/air entrainment effects, and experimental verification of these effects has not been adequately demonstrated.

8. It was not possible within the limits imposed by this

review to evaluate the accuracy of the predictions published by SAI. Rather, the author has reviewed the methodology described by SAI and believes that such techniques hold the most promise for accurate prediction of vapor dispersion from catastrophic spills on water. A program designed to evaluate the accuracy of the SAI model or other models of similar generality should now be considered high priority. The Recommendations section of this report addresses this need.

XI. RECOMMENDATIONS

1. The Science Applications, Inc. (SAI) LNG vapor dispersion model should be more thoroughly evaluated. This will require the cooperation of SAI due to the proprietary nature of their computer programs which are required for solution of the model equations. Further evaluation of the SAI model, or other similar models based on simultaneous solution of the mass, momentum and energy balance equations which may become available, should address the following requirements:

   a. The methodology of describing turbulent mass, momentum and energy transfer should be critically evaluated. A literature search should be conducted to identify and evaluate experimental data supporting the assumption of first-order (eddy diffusivity, thermal conductivity and viscosity) turbulent transfer phenomenological relationships for describing turbulent transfer in the lower atmosphere.

   b An error analysis should be done to provide some means for estimating the confidence level in the technique used to assign numerical values to the turbulent transfer coefficients.

   c. Sufficient calculations should be made with the model to determine the sensitivity of the results predicted by the model to uncertainties in the transfer coefficients identified in b. above.

   d. An analysis should also be made of the liquid spread, vapor generation, and heat transfer models used in the

specification of the boundary conditions to determine the sensitivity of the model predictions.

e. The numerical stability and accuracy of the algorithm used for computer solution of the equations should be critically evaluated.

2. A series of computations should be made, using the SAI model, of the downwind distance to the time average 5% concentration level for "instantaneous" LNG spills as a function of spill size. The range of spill sizes should be from 10 cubic meters to 25,000 cubic meters with sufficient points between to adequately characterize the predicted relationship between flammable cloud travel and spill size.

3. The result of 2 above should be compared with a similarly prepared relationship between flammable cloud travel and spill size predicted using the Germeles and Drake model described in this report. It is anticipated that the results will be in substantial agreement for very small spill sizes but the comparison should indicate the smallest spill sizes for which significant differences appear in predicted downwind distance. Such a comparison should also provide guidance for determining a lower bound on the size of experimental spills which may be required to assess large spill behavior.

4. In ancitipation of experimental spills which may be required to provide confidence in predictions of large spill behavior, an evaluation should be made of the experimental data requirements associated with verification of model predictions.

5. Additional experimental spills should be performed only after completion of the program outlined above, and such spills should be performed for the purpose of model evaluation. Large "demonstration spills" have been suggested recently, largely as a result of the variation in predictions which has been the subject of this report. It is the opinion of this author that validation of models should still be the primary goal of further test programs; "demonstration" of the effects of large spills without heavy reliance on models should be avoided.

LITERATURE CITED

1. Burgess, D. S., J. N. Murphy, and M. G. Zabetakis, "Hazards of LNG Spillage in Marine Transportation," U. S. Bureau of Mines, Performed for the U. S. Coast Guard (NTIS AD-705078) (1970).

2. Burgess, D. S., J. Biordi, and J. Murphy, "Hazards of Spillage of LNG into Water," U. S. Bureau of Mines, Performed for the U. S. Coast Guard (NTIS AD-754498) (1972).

3. Feldbauer, G. F., J. J. Heigl, W. McQueen, R. H. Whipp, and W. G. May, "Spills of LNG on Water - Vaporization and Downwind Drift of Combustible Mixtures," Esso Research and Engineering Company Report No. EE61E-72 (Performed for the American Petroleum Institute) (24 November 1972).

4. Germeles, A. E. and E. M. Drake, "Gravity Spreading and Atmospheric Dispersion of LNG Vapor Clouds," Fourth International Symposium on Transport of Hazardous Cargoes by Sea and Inland Waterways, sponsored by U. S. Department of Transportation (U. S. Coast Guard), Jacksonville, Florida 26-30 October 1975.

5. Raj, P. P. K. and A. S. Kalelkar, "Assessment Models in Support of the Hazards Assessment Handbook (CG-446-3)," prepared for DOT, U. S. Coast Guard January 1974 (NTIS AD 776617).

6. Fay, James A. and David H. Lewis, Jr., "The Inflammability and Dispersion of LNG Vapor Clouds," Fourth International Symposium on Transport of Hazardous Cargoes by Sea and Inland Waterways, Sponsored by U. S. Coast Guard, Jacksonville, Florida 26-30 October 1975.

7. "DRAFT Environmental Impact Statement For the Construction and Operation of an LNG Receiving Terminal at Los Angeles, California, Volume II," Federal Power Commission, Western LNG Terminal Associates Docket No. CP 75-83-2 (September 1976).

8. "LNG Terminal Risk Assessment Study for Oxnard, California," Science Applications, Incorporated, 1200 Prospect Street, La Jolla, California 92037, prepared for Western LNG Terminal Company, 720 West Eighth Street, Los Angeles, California 90017, (December 22, 1975).

9. Boyle, G., and Kneebone, "Laboratory Investigations into the Characteristics of LNG Spills and Water: Evaporation, Spreading and Vapor Dispersion," Shell Research LTD. (available from American Petroleum Institute, Washington, D. C.).

10. "Gadilla LNG Jettison Test," 3 July 1973, "Preliminary Report."

11. Kneebone, A. and L. R. Prew, "Shipboard Jettison Test of LNG onto the Sea," presented at Gastech '74, Amsterdam (13-14 November 1974).

12. Pasquill, F., Atmospheric Diffusion, 2nd Edition, Halstead Press, division of John Wiley and Sons, Incorporated, New York (1974).

13. Slade, D. H., Meteorology and Atomic Energy 1968, TID-24190, National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

14. Fay, J. A. "Physical Processes in the Spread of Oil on a Water Surface," in Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D. C.(1970).

15. Raj, P. P. K. and A. S. Kalelkar, "Fire-Hazard Presented by a Spreading, Burning Pool of LNG on Water," 1973 Fall Meeting, Western States Combustion Institute.

16. Hoult, D. "The Fire Hazard of LNG Spilled on Water," Proceedings of Conference on LNG Importation and Safety, Sponsored by the U.S. Coast Guard, Boston, Mass. (1972).

17. (in) Otterman, B., "Analysis of Large LNG Spills on Water, Part I: Liquid Spread and Evaporation," Cryogenics, August 1975, pp 455-460.

18. Otterman, B., "Analysis of Large LNG Spills on Water, Part I: Liquid Spread and Evaporation," Cryogenics, August 1975, pp 445-460.

19. Muscarri, (Cited in) Environmental Impact Statement - See Reference 7.

20. Hogstrom, U., "An Experimental Study on Atmospheric Diffusion," TELLUS XVI (1964), 2,pp206-251.

21. Singer I. A., and M. E. Smith, "Atmospheric Dispersion at Brookhaven Laboratories," Air and Water Pollution International Journal, 10,pp125-135 (1966).

22. Yih, C. S., Dynamics of Nonhomogeneous Fluids, MacMillan, New York (1965).

23. Fay, J. A., "Physical Processes in the Spread of Oil on a Water Surface," in Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D. C. (1970).

24. Fay, J. A., "Unusual Fire Hazard of LNG Tanker Spills," Combustion Science and Technology, 1,pp47-49 (1973).

25. Zimmerman, J. R., and R. S. Thompson, "User's Guide For HIWAY, a Highway Air Pollution Model," EPA Report No. EPA 650/4-74-008 (February 1975)

26. Holland, J. E., "A Meteorological Survey of the Oak Ridge Area," p. 540, Atomic Energy Commission Report ORO-99, Washington, D. C.

27. Turner, D. B., Workbook of Atmospheric Dispersion Estimates, U. S. Public Health Service Publication No. 999-AP-26.

28. Personal Communication with W. England, and A. Boni, Science Application, Inc.

29. Hanna, S. R., "A Method of Estimating Vertical Eddy Transport in the Planetary Boundary Layer Using Characteristics of the Vertical Velocity Spectrum," Journal of the Atmospheric Sciences, 25,pp1026-1033 (1968).

30. Lumley, J. and H. Panofsky, The Structure of Turbulence, New York Interscience Publications (1964).

31. Taylor, R. J., J. Warner, and N. E. Bacon, "Scale Length in Atmospheric Turbulence as measured from an Aircraft," Quarterly Journal Royal Meteorological Society, 96,pp750-755 (1970).

32. Smith, T. B., and B. L. Niemann,"Shoreline Diffusion Program: Oceanside, California, Vol I., Technical Report." Final Report by Meteorological Research, Incorporated, to Deseret Test Center, Ft. Douglas, Utah, Contract No. DA-42-007-AMC-180 (R).

33. Smith, F. B., and S. M. Howard, "Methodology for Treating Diffusivity," Meteorology Research Incorporated Report, (September, 1972).

34. "LNG Safety Program Interim Report on Phase II Work," American Gas Association Project IS-3-1,(July, 1974).

35. Bradshaw, P., "The Understanding and Prediction of Turbulent Flow," Aeronautical Journal, July 1972.

36. Lewellen, W. S. and M. Teske, "Turbulence Modeling and its Application to Atmospheric Diffusion, Part I: Recent Program Development Verification, and Application," EPA Report No. 600/4-75-016 a,(December 1975).

37. Lewellen, W. S. and M. Teske, "Turbulence Modeling and its Application to Atmospheric Diffusion, Part II: Critical Review of the Use of Invariant Modeling," EPA Report No. 600/4074-016 b,(December 1975).

38. Pasquill, F., "The Estimation of the Dispersion of Windborne Material," Meteorological Magazine 90,(1 February 1961).

39. Lind, C. D., "Explosion Hazards Associated with Spills of Large Quantities of Hazardous Materials," Phase I, U. S. Coast Guard Report No. CG-D-30-75, NTIS AD A001242, (Oct. 1974).

40. Lewis, D. H., Jr., "The Dispersion and Ignitibility of LNG Vapor Clouds", M. S. thesis, Massachusetts Institute of Technology,(June 1974).

41. Fannelop, T. K. and Waldman, G. D., "Dynamics of Oil Slicks", AIAA Journal, 10 (1972).

42. Fay, James A., Personal Communication, See Appendix II of this report.

APPENDIX I
DISPERSION COEFFICIENT DATA FOR
USE IN CLASSICAL AIR POLLUTANT
DISPERSION EQUATIONS

Dispersion coefficient data are of two types:

1. Data representing the cloud width (or specified fraction thereof) as a function of distance traveled by an instantaneous release of material from a point source. Data of this type is relatively limited. A survey of data of this type has been made by Slade (13) from which the suggested correlations shown in Tables A-I-1 were proposed.

TABLE A-I-1

SUGGESTED ESTIMATES FOR σ_{yI} AND σ_{zI}, SLADE (13)

Parameter	Conditions	x=100 meters	x=4000 meters	Approximate Correlation
σ_{yI}, meters	Unstable	10	300	$0.14\ X^{0.92}$
	Neutral	4	120	$0.06\ X^{0.92}$
	Very Stable	1.3	35	$0.02\ X^{0.89}$
σ_{zI}, meters	Unstable	15	220	$0.53\ X^{0.73}$
	Neutral	3.8	50	$0.15\ X^{0.70}$
	Very Stable	0.75	7	$0.05\ X^{0.61}$

It should be noted almost no data were reported by Slade for distances beyond about 4000 meters, and the approximate correlations for dispersion coefficients as a function of distance were

in the range 100 to 4000 meters.

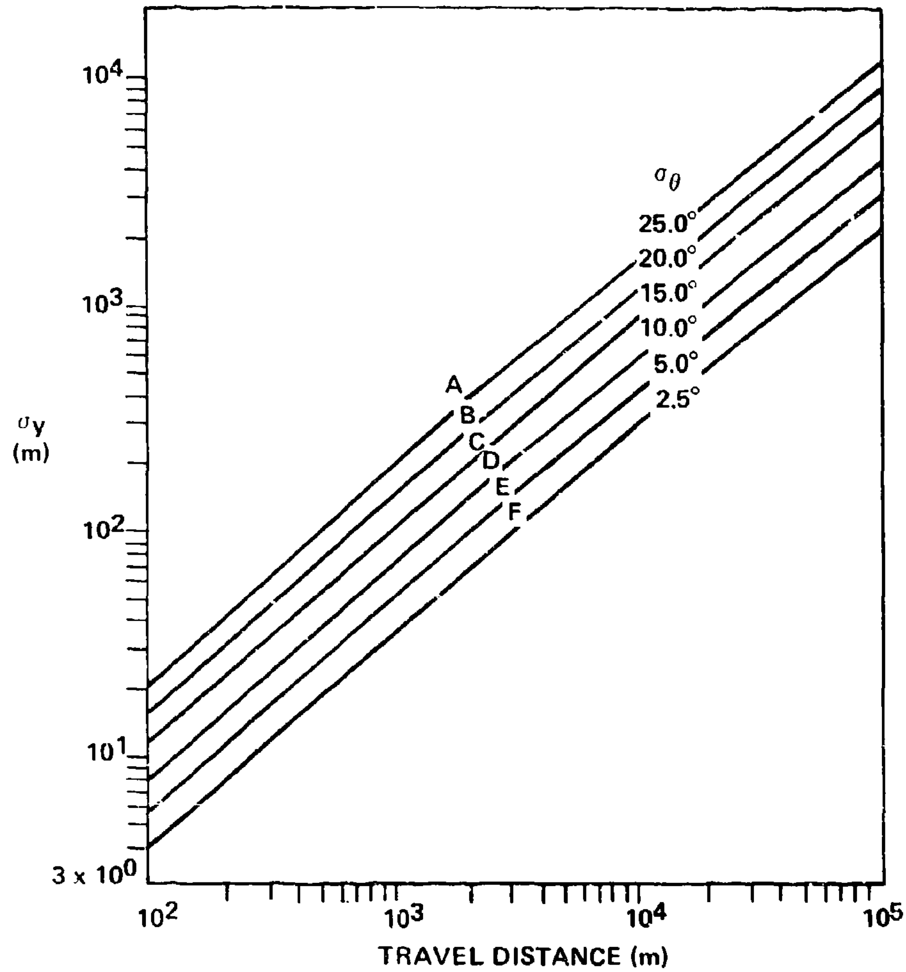
2. Dispersion coefficient data representing the standard deviation of the horizontal concentration distribution, σ_y, and the standard deviation of the vertical concentration distribution, σ_z, as functions of travel distance from a steady, continuously emitting point source. The horizontal and vertical coefficients, σ_y, and σ_z respectively, used by all investigators have been obtained from two primary sources.

DISPERSION COEFFICIENTS PUBLISHED BY PASQUILL (12)

Pasquill and others published, around 1960, estimation methods for σ_y and σ_z which were based on measurements of wind-direction fluctuation. Due to the need for estimates of dispersion coefficients when wind fluctuation measurements are not available, Pasquill suggested values for σ_y and σ_z based on the degree of atmospheric stability. He further suggested that stability be estimated from wind speed and insolation. The correlations proposed by Pasquill, along with the guidelines for estimating atmospheric stability, are shown in Figures A-I-1 and A-I-2.

DISPERSION COEFFICIENTS PUBLISHED BY SINGER AND SMITH (21)

Singer and Smith published estimation methods for σ_y and σ_z derived from measurements of dispersion of oil fog, radioactive isotopes and uranine dye at the Brookhaven National Laboratory.



RELATION OF PASQUILL TURBULENCE TYPES TO WEATHER CONDITIONS

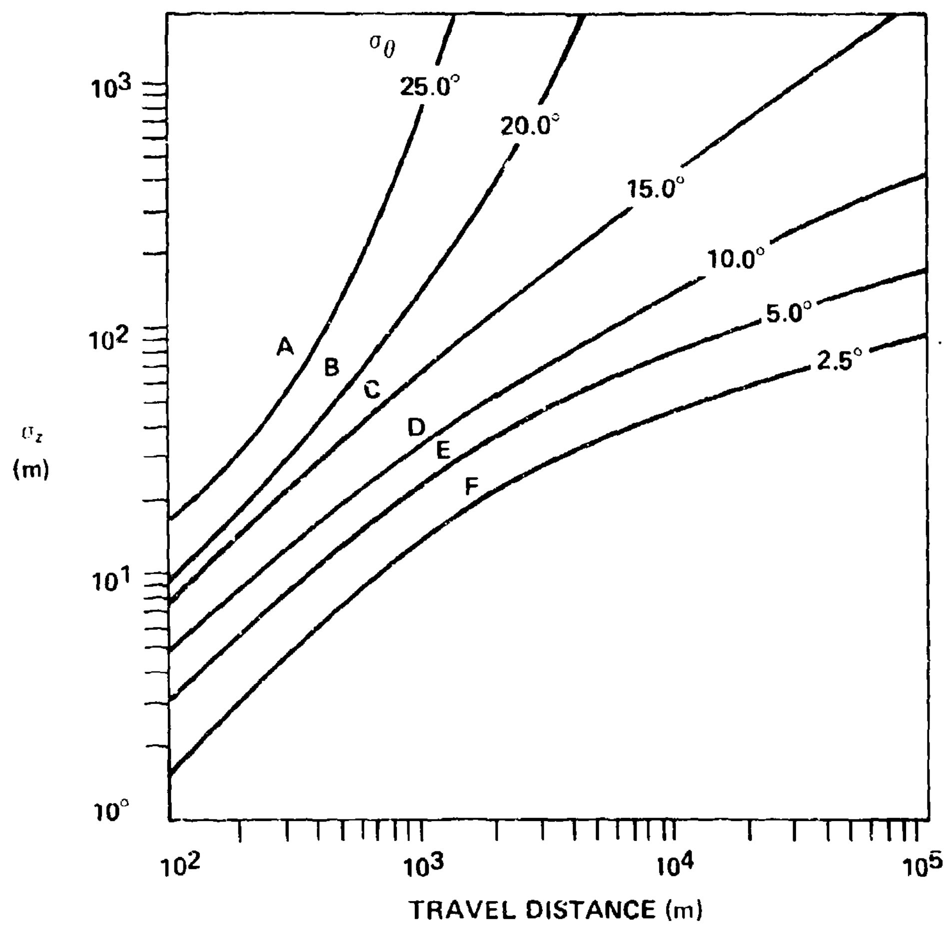
A – Extremely unstable conditions
B – Moderately unstable conditions
C – Slightly unstable conditions
D – Neutral conditions*
E – Slightly stable conditions
F – Moderately stable conditions

Surface wind speed, m/sec	Daytime insolation			Nighttime conditions	
	Strong	Moderate	Slight	Thin overcast or ≥ 4/8 cloudiness †	≤ 3/8 cloudiness
<2	A	A-B	B		
2	A-B	B	C	E	F
4	B	B-C	C	D	E
6	C	C-D	D	D	D
>6	C	D	D	D	D

* Applicable to heavy overcast, day or night

† The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon that is covered by clouds.

Figure A-I-1. HORIZONTAL DISPERSION COEFFICIENTS BY PASQUILL



RELATION OF PASQUILL TURBULENCE TYPES TO WEATHER CONDITIONS

A – Extremely unstable conditions
B – Moderately unstable conditions
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Surface wind speed, m/sec	Daytime insolation			Nighttime conditions	
	Strong	Moderate	Slight	Thin overcast or ≥ 4/8 cloudiness †	≤ 3/8 cloudiness
< 2	A	A-B	B		
2	A-B	B	C	E	F
4	B	B-C	C	D	E
6	C	C-D	D	D	D
> 6	C	D	D	D	D

* Applicable to heavy overcast day or night

† The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon that is covered by clouds.

Figure A-I-2. VERTICAL DISPERSION COEFFICIENTS BY PASQUILL

The most important sources of data were oil fog release experiments, which involved emission of oil fog droplets from a single source at an elevation of 108 meters. In addition measurements of radioactive isotope (A^{41}) emission from the Brookhaven Graphite Research Reactor were used to make "qualitative or at best crude quantitative" estimates of plume position and dimension. The source height in this case was also 108 meters. These experiments were apparently the basis for estimation of horizontal and vertical dispersion coefficients at great distances from the release point, and all information at distances 50 km or more was obtained from the isotope measurements. Uranine dye releases from a height of 2 meters also provided a small amount of data. In all cases, concentration data were mean values obtained over periods ranging from 30 to 90 minutes. The atmospheric stability was taken into account by defining 5 "gustiness classifications" based on horizontal wind direction fluctuations measured at the release site with a Bendix Friez Aerovane located 350 ft (107 meters) above ground. The definition of these "gustiness classifications" is shown below.

Gustiness Classification	Horizontal Wind Direction Fluctuation
A	Fluctuations of wind direction $> 90^\circ$
B_2	Fluctuations ranging from 40° to 90°
B_1	Fluctuations ranging from 14° to 45°
C	Fluctuations ranging from 0 tc 15°
D	Essentually no fluctuation, short term fluctuation do not exceed 15°

The correlation for the horizontal dispersion coefficient, σ_y, developed from the data is shown in Figure A-I-3. No correlation was developed for Type A Gustiness Classification since the condition is characterized by the absence of organized horizontal wind flow and is describable only in qualitative terms.

The vertical structure of the plumes from test releases was not measured directly; the vertical dispersion coefficients were calculated from Equation V-12 rearranged:

$$\sigma_z = \frac{Q'}{\pi \sigma_y \bar{u} C_{x,y=0,z=0}}$$

The correlation for the vertical dispersion coefficient, σ_z, proposed by Singer and Smith are shown in Figure A-I-4. In contrast to the correlation proposed by Pasquill, et. al, the Bro[illegible]ven vertical dispersion coefficient vs. distance is [illegible]ted as being of the form $\sigma=ax^b$, similar to the [illegible]e[illegible]on for the horizontal dispersion coefficient. Smith and Pasquill presented plots of typical field concentrations against distance which show reasonable agreement with predictions using their dispersion coefficient correlations out to about 6000 meters. Singer and Smith emphasized the lack of precision in the definition and specification of the vertical dispersion coefficient, which are tied by the method of determination using Equation V-12 to the assumption of constant wind speed, as well as the assumed correctness of the model.

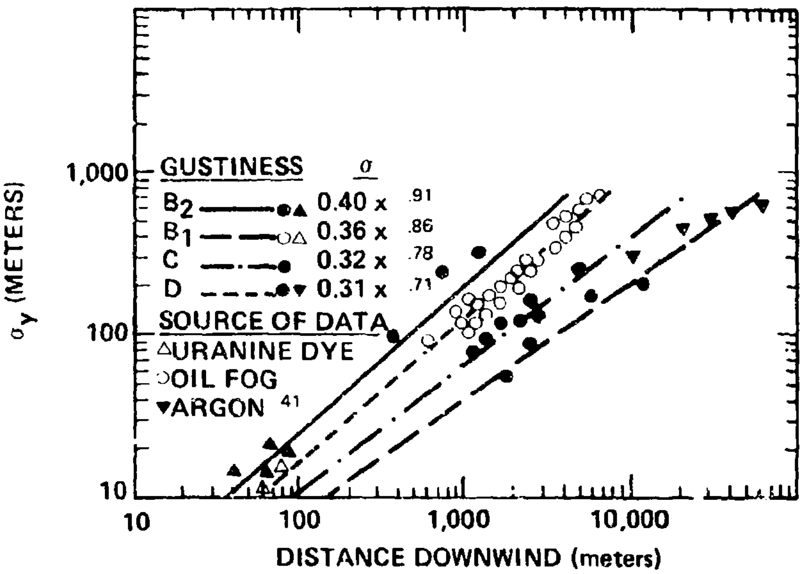

Figure A-I-3. HORIZONTAL DISPERSION COEFFICIENTS BY SINGER AND SMITH (21)

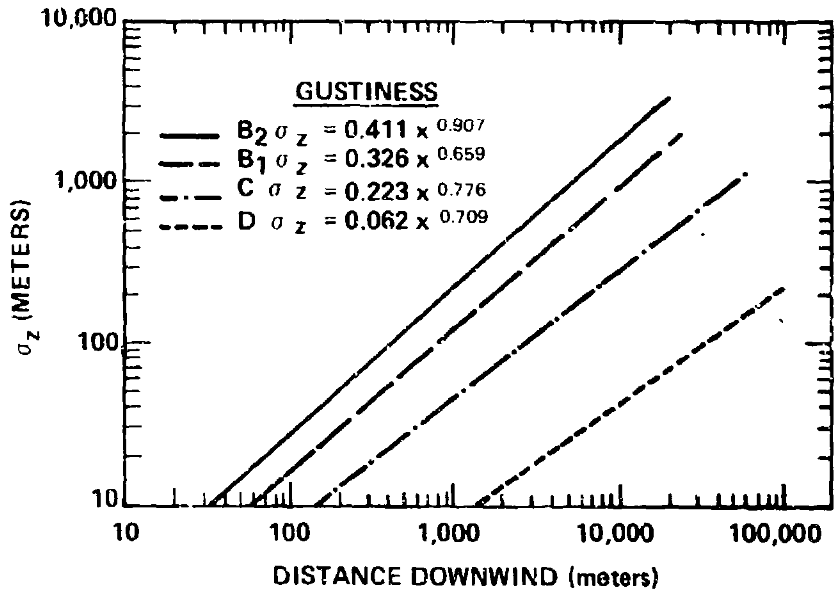

Figure A-I-4. VERTICAL DISPERSION COEFFICIENTS BY SINGER AND SMITH (21)

For comparison the correlations for σ_y and σ_z proposed by Pasquill and Singer and Smith are plotted together on Figures A-I-5 and A-I-6.

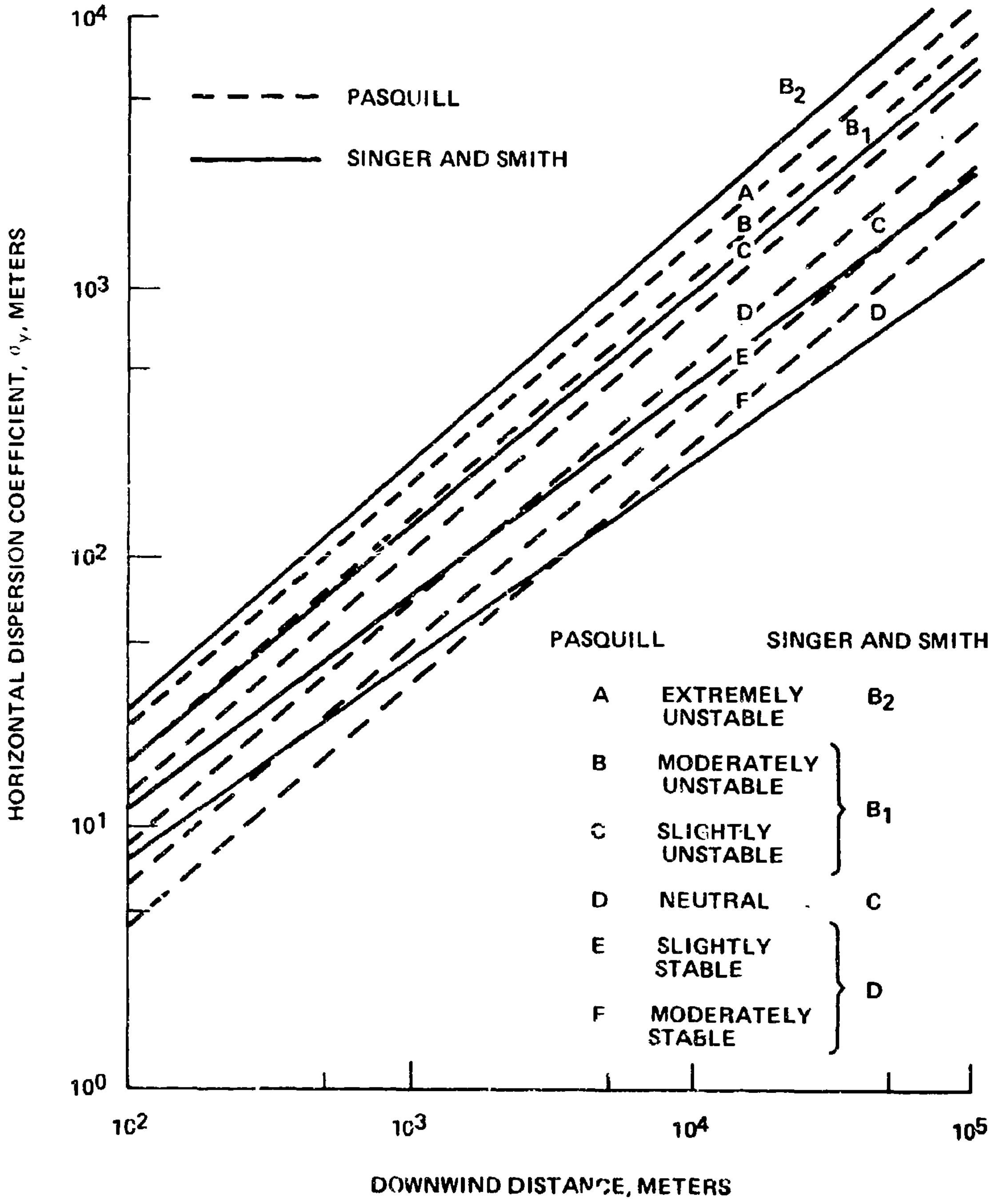

Figure A-1-5. COMPARISON OF PASQUILL AND SINGER AND SMITH COEFFICIENTS

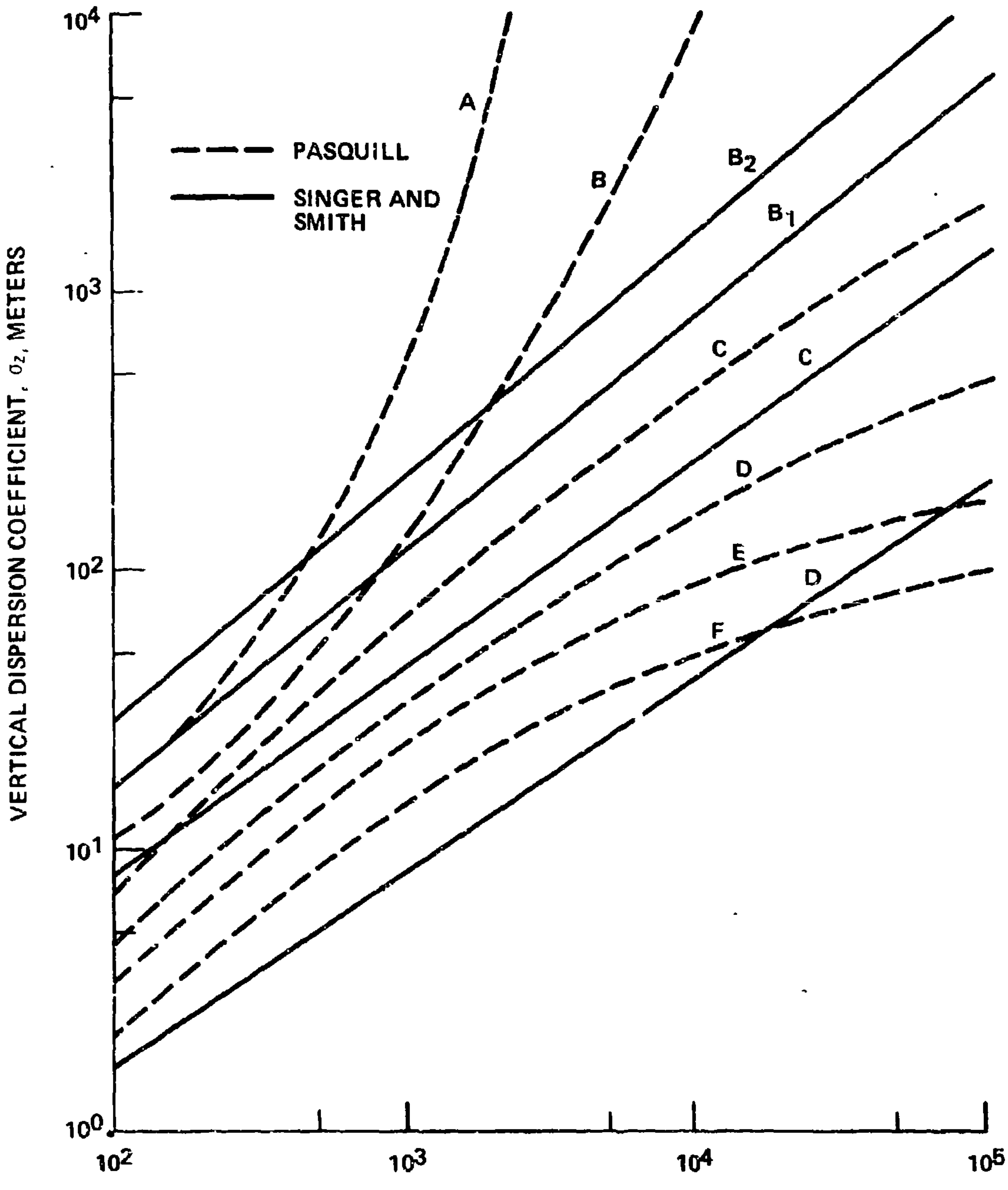

Figure A-I-6. COMPARISON OF PASQUILL AND SINGER AND SMITH COEFFICIENTS

APPENDIX II

REQUEST FOR COMMENTS

AND

COMMENTS ON DRAFT REPORT

DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD

MAILING ADDRESS:
U.S. COAST GUARD (G-MHM/83)
WASHINGTON, D.C. 20590
PHONE: (202)-426-2306

10330/4-2/1
4 February 1977

To: Distribution*

Gentlemen:

I am enclosing a copy of my draft report, "Predictability of LNG Vapor Dispersion from Catastrophic Spills onto Water: An Assessment," prepared for the Cargo and Hazardous Materials Division, Office of Merchant Marine Safety, U. S. Coast Guard. This report represents my understanding and assessment of frequently cited predictions of hazardous vapor cloud travel which might occur in the event of a catastrophic accident involving a marine LNG carrier. My description of the technique used to make these predictions, and the calculations based on those techniques, are based on reports prepared by the investigating groups which developed the modeling techniques. In some instances, these groups have, at my request, provided assistance in this effort. Such assistance involved discussions to clarify questions which I had based on my review of the published reports cited in the report, as well as provision of computer codes allowing me to make predictions of my own utilizing each of the models. However, the description of the models and the associated predictions were prepared by me. I have purposely not included the Conclusions and Recommendations sections and the Summary (which includes same). I consider these sections tentative until such time as I have received your comments on the accuracy of my technical review of this problem.

It is my intention to recommend the release, by the U. S. Coast Guard, of the completed report to all interested parties. I hope that it will be helpful in answering some of the questions which prevail in the area of safety management in LNG transportation.

I respectfully request your review, as a representative of the investigating groups whose work I have discussed, of the technical and interpretive accuracy of my description of your model and the associated predictions. It is my intention to make your comments, and any revisions or rebuttals which may be indicated, a part of the final report.

In the interest of releasing the final report as soon as possible, please send me your written comments, in form suitable

for subsequent inclusion, by 25 February 1977. Please feel free to call me if I can clarify any point in the report or its intended development to final form.

Sincerely,

Jerry Havens

JERRY HAVENS
Technical Advisor
Cargo and Hazardous
Materials Division

Encl: (1) Draft Report, "Predictability of LNG Dispersion from Catastrophic Spills Onto Water: An Assessment"

*Distribution:
Dr. David S. Burgess
Pittsburgh Mining Safety and Research Center
U. S. Bureau of Mines
4800 Forbes Avenue
Pittsburgh, PA 15213

Dr. Walter May
Exxon Nuclear Co., Inc.
Plains Road
Ballston Spa, New York 12020

Mr. Don Oakley
Distrigas Corporation
125 High Street
Boston, MA 02110

Professor James Fay
Room 3-246
Massachusetts Institute of Technology
Cambridge, MA 02139

Dr. Theodore Needles
Federal Power Commission
825 North Capital Street, N.E.
Washington, D.C. 20426

Dr. Walter England
Science Applications, Inc.
1200 Prospect Street
P.O. Box 2351
La Jolla, CA 92037

Mr. Donald Allen
Arthur D. Little, Inc.
Acorn Park
Cambridge, MA 02140

United States Department of the Interior

BUREAU OF MINES

4800 FORBES AVENUE
PITTSBURGH, PENNSYLVANIA 15213

Pittsburgh Mining and Safety Research Center

February 25, 1977

Dr. Jerry Havens
Technical Advisor
Cargo and Hazardous Materials Division
U. S. Coast Guard (G-MHM/83)
Washington, DC 20590

Dear Jerry:

I have read your manuscript quite carefully and find nothing to which I can object. You have performed a useful service for the many people who still ask questions about atmospheric dispersion.

Sincerely yours,

Dave

David Burgess
Research Supervisor
Fires and Explosions

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March 7, 1977

Mr. Jerry Havens
Technical Advisor
Cargo and Hazardous Materials Division
Department of Transportation
U.S. Coast Guard
Washington, D.C. 20590

Dear Mr. Havens:

I appreciate the opportunity of commenting on your Draft Report on LNG Vapor Dispersion. My comments are attached.

I feel that the review and comparison you have carried out is a very useful study.

I indicated during our telephone conversation that I had written a paper on the "unmixed" character of an LNG vapor/air plume. A copy is attached. I also attach a handwritten derivation of the Pasquill equation, as promised in our phone conversation. I hope you can read it.

Very truly yours,

W. G. May

W.G. May
Senior Scientific Advisor

/dp

cc: W. McQueen (w/attachments)

Attachments: Paper
Derivation
Comments

COMMENTS: "Predictability of LNG Vapor Dispersion from Catastrophic Spills Onto Water: An Assessment".

First, it is interesting to see a direct comparison of the models that have been suggested for LNG-dispersion, particularly the comparisons of Table IV-1. The number that is quoted for our analysis, 5.2 miles, is a little shorter than we would have anticipated (7.6 miles). We never calculated results for such a large spill however, 25000 m^3; our largest (calculation) was a 4000 m^3 spill. I believe that Mr. Havens has followed our procedure correctly, so that his number of 5.2 miles is to be preferred over our simple extrapolation.

I agree with Dave Burgess that the lack of historical perspective in the Report is unfortunate. I am proud of the work that we did and feel strongly that some of the later analyses borrowed heavily from it. But in the absence of any historical comment, the old analyses have to suffer.

I have several comments concerning the presentation of our analysis, where either I don't agree, or I feel that useful comparisons with others could have been drawn.

1. The Report assigns us to the category of those using a "steady-state" model, and states that we have used our measurements of "maximum vapor flow rate - as an estimate of Q in Eq. VII-5". I believe that this doesn't do justice to what we did, and certainly carries an implication that I don't agree with.

   First, it is important to understand Eq. VII-5, the "Pasquill" equation. It is easily derived, starting from an assumption that concentrations follow a Gaussian distribution. The equation is simply a material balance, which relates the amount flowing at any instant to the plume velocity and the concentration level. [The amount flowing is calculated as the amount crossing a plane at right angles to the direction of the wind. Axial diffusion is neglected - an important consideration discussed later].

   The important point is that the "Q" in the Pasquill equation <u>is</u> the vapor flow rate. The vapor flow rate is not an "<u>estimate</u>" for Q; it <u>is</u> Q. We didn't estimate "Q", we <u>measured</u> it. People <u>who</u> equate the evaporation rate to Q <u>are making</u> an "estimate".

   For steady state spills, of course, the value of "Q" (vapor flow rate) is the same as evaporation rate. But for instantaneous spills it is not; measurements showed this, and elementary thinking suggests it is not. [What value do you assign to Vapor Flow Rate as wind speed approaches zero?].

2. I think it worthwhile to compare our use of the Pasquill equation with the "Puff" model (Eq. V-10). I do not believe that the major difference is "unsteady state" vs. "steady-state". Our analysis was certainly not a "steady-state analysis. Our values for "Q" were transient (i.e. never reached steady-state), and were in general a long way from the evaporation rate (i.e., the value that would be used in a steady-state analysis).

The important distinction, it seems to me, is the way that axial dispersion is handled. The "Puff" model incorporates an axial dispersion factor; that is, the plume lengthens out as it goes downwind (while spreading as well). We did not use an axial dispersion factor; our plume was pictured as keeping the same length that it had at the point where we measured it (i.e., at our line of sensors). I consider this a weakness in our model, an advantage for the "Puff".

There are'pros' as well as 'cons', however. There is difficulty getting the Puff model started in a sensible way. Undoubtedly, the plume from a large instantaneous spill will be stretched out alot immediately downwind of the spill point. The wind simply cannot drag away the gas as fast as it is evolved, and a large cloud accumulates; particularly at low wind speed. An instantaneous spill would never start off downwind as a round Puff. Our use of a measured "Q" has an advantage in this respect; the measured "Q" is the resultant of alot of complex interactions: the wind attacks the accumulation at the spill point;the spill is not quite instantaneous; some stretching of the plume has occurred in flowing from the spill point to the point where the measurement was made.

I believe that most of the stretching out of the plume is a consequence of the initial conditions (the accumulation of vapor over the spill point) - particularly at low wind speed. I don't think the Puff Models handle this very well, while some evaluation of it appears automatically in our measurement and use of vapor flow rate Q.

I hadn't seen the Germeles and Drake, and the Fay, Puff Models before the Coast Guard write-up. I have tried to compare them with ours (particularly the Germeles and Drake model), and some comments are given below. But first, it seems to me helpful to give a little historical perspective.

There were two general approaches for plume analysis at the time we did our work. One attributed the plume spread to gravity effects. The assumption was generally made that the density of LNG vapor/air mixtures was about linear with composition (for adiabatic conditions). The other approach simply used the standard dispersion due to the weather.

We and the Bureau of Mines (at about the same time), calculated the effect of air humidity on the mixture density; the profound effect that was found made the first assumption (above) untenable. Simply assigning the observed results to weather was also untenable, however; the plumes were much too low and wide. This led us then to the analysis which includes an effect of both; the gravity effect controls initially, but as the plume is diluted and its density approaches that of air, the final mixing is assigned to the weather.

Apparently the Germeles and Drake, (as well as Fay?) models follow this same plan. There are differences in details - e.g., the criterion used for switching from "gravity" spread to"weather" spread, and others - but the general approach is the same.

Some of the similarities and differences between our analysis and the later Germeles and Drake analysis are outlined below:

a. The gravity spread relationships used are essentially the same (they differ by a constant coefficient).

We started with a relationship (Fannelop and Waldman):

$$L = k\ x\ (\frac{\Delta\rho}{\rho}\ ghLu)^{1/3}\ x^{2/3}\ \frac{1}{u}$$

We differentiated with respect to x, to get the change of width with distance, while allowing for changing conditions in the plume (i e., the analysis keeps track of plume temp. density, composition, dimensions, just as the Germeles and Drake model does).

$$\frac{dL}{dx} = k\ x\ (\frac{\Delta\rho}{\rho}\ gh)^{1/3}\ (\frac{L}{x})^{1/3}\ (\frac{1}{u})^{2/3}$$

If instead, we had differentiated with respect to time, while making tne assumption that velocity is constant so that distance and time are related (x = ut), we would have obtained the Germeles and Drake gravity spread (Eq. VI-11)

$$\frac{dR}{dt} = k^{3/2}\ (\frac{\Delta\rho}{\rho}\ gh)^{1/2}$$

The only difference between our analysis and that of Germeles and Drake is the constant coefficient; [we would get 18.5 for the G&D spread equation, compared with their 29.11]. I believe that there are questions about the Fannelop and Waldman analysis and its application to this work, so that the "right" coefficient is uncertain [see the article by Hoult in Rev. of Fl. Mech.). [Incidentally, the Coast Guard Report gives different equations for the G&D spread rate, pp. 49 and 51.. I assume the one on p. 51 is correct].

b. In our analysis, we maintain the plume height constant during the gravity spread. This has the effect of specifying, indirectly, a mixing coefficient. The procedure may appear arbitrary but was based on experimental observation; our plumes appeared to rise very little during their downwind travel. The Germeles-Drake analysis introduces a mixing coefficient. I note however, in the example given in the Coast Guard report, that the plume height for a 25000 m^3 spill increased only a very small amount during the gravity-spread portion of its travel; the increase was from 13 m to 18m, over a downwind distance that was presumably several miles. I consider that to be in very close agreement with our observation of constant plume height. The mixing rates of the two studies must be very close.

3. We assign a downwind speed to the plume which varies with concentration; my impression - perhaps incorrect - is that the Germeles-Drake analysis assigns constant (wind) speed.

The Coast Guard report unfortunately does not give our rationale for varying plume speed: we calculated conservation of momentum, assuming no pressure effects. At high concentration, near the source, the velocity is therefore low, but approaches wind speed at large dilution.

The experimental data confirm this type of effect. The average plume speeds measured have always been lower than the wind speed, by substantial factors, e.g., 3. I consider our approximation more acceptable than an assignment of a constant speed, equal to the wind.

4. We have apparently used somewhat different coefficients than Germeles and Drake for our analysis of the effect of weather. The important coefficient (at least in our analysis), is the vertical coefficient, σ_z. The plumes are already so wide at the end of the gravity spread that further spreading at the edges due to the weather, is not very significant. Our vertical coefficient (Singer and Smith "D"), is a little more stable than the Gifford-Pasquill "F" category used by Germeles and Drake. [Incidentally, the recent Brookhaven data show stabilities that exceed Pasquill F by a factor of 2, for example].

The Coast Guard report comments on our use of mixed weather coefficients. When we did our tests there were essentially no data for mixing over water. If we had applied the meteorological data in the usual way (i.e., lapse rate, wind speed, etc.), the weather during our tests would have generally been classified category "C", slightly unstable. But we recognized that this was not the case; our plumes behaved as though the weather was much more stable than that. We concluded that weather over water was simply different than over land, generally much more stable. The Brookhaven data* have become available since that time and confirm the high degree of stability. The BNL report also points out that application of land-based weather correlations to predict stability over water will give large errors - just as we had concluded earlier.

We chose the spread coefficients that we did simply because we thought they matched our data best. We would not want to claim any great generality for them, [See p. 72 of the Coast Guard Report]. If we were doing the work again, we would make use of the data that have since been measured over water.

5. A few other general comments on the Coast Guard Report:

   a. Table VI-1 shows correlations for maximum pool sizes. I suggest that my ASME paper would be a useful addition. Opinions may vary as to the quality of that paper, but it does have one major advantage - it contains data, all of the data that were available at the time it was written. Further, the data cover the impressive range of spill size from 5 to 10,000 lbs.

      I'm not familiar with all the references cited in Table VI-1, but those that I recognize represent early theoretical studies, done before data was available. Some of the early theory has been proven wrong by later experimental work.

   b. The SAI analysis appears to be a significant contribution but really needs critical evaluation.

      It seems obvious to ask that the analysis should be checked against experimental data. To my knowledge, it has been used to check our Run 11 (relatively high wind speed, 18 mph), and gives a fair check - not an exact check by any means. I would like to see it checked against other data, particularly at lower wind speed

---

*"Studies of Atmospheric Diffusion from a Near-Shore Oceanic Site," Raynor, Michael, Brown & Sethuraman, BNL 18997, June, 1974.

(e.g., our Run 10 at 5 mph). Interestingly, the SAI calculations show an effect of wind speed that is opposite to the small scale experimental data. It is important to see if this occurs in the analysis only for larger spills.

I have to say that the SAI calculated result presented in Table IV-1, a distance of 1.2 miles for a 37,500 cu.m. spill, seems highly improbable to me. It just looks unreasonable when plotted alongside the measured data. Their value of 3.75 miles for a 15 m/s wind speed appears much more acceptable. Check calculations against the existing data would lend some confidence. Final answers will probably await larger tests.

BILLERICA TECHNICAL CENTER

CABOT CORPORATION CONCORD ROAD, BILLERICA, MASSACHUSETTS 01821

CABLE ADDRESS "CABLAK" BOSTON
TELEPHONE: BILLERICA—272-3800
AREA CODE
617 VIA BOSTON—482-6000

March 25, 1977

Dr. Jerry R. Havens
c/o U. S. Coast Guard
Hazardous Materials Division
Room 8308
Washington, D. C. 20590

Dear Dr. Havens:

Please find enclosed comments on your draft report entitled "Predictability of LNG Vapor Dispersion from Catastrophic Spills onto Water: An Assessment", January 1977.

The comments were prepared in the main by Drs. A. E. Germeles and F. Feakes. We thank you for the opportunity to comment.

Yours truly,

R E Morton, VP

for: Donald W. Oakley
President, Distrigas Corporation

DWO/gh

COMMENTS BY A. E. GERMELES AND F. FEAKES ON THE DRAFT REPORT "PREDICTABILITY OF LNG VAPOR DISPERSION FROM CATASTROPHIC SPILLS ONTO WATER: AN ASSESSMENT", PREPARED BY J. A. HAVENS FOR U.S.C.G. (JANUARY 1977)

We wish to thank the Coast Guard for the opportunity to comment on the draft report "Predictability of LNG Vapor Dispersion from Catastrophic Spills onto Water: An Assessment", by Jerry A. Havens. Dr. Havens' contribution helps reduce the confusion that has developed concerning this subject. It is welcomed because it is clear that the differences and errors in models have lead to overemphasis of the question of "How far will LNG vapor travel?"

We have one major comment, and several of a more technical nature. The main comment relates to Tables IV-1 and VI-3 where the Cabot model based on the work of Germeles-Drake is used with F weather to compute a downwind distance of about 10 miles for a 25,000 m^3 instantaneous spill. Cabot's experience is clear. The U. S. Coast Guard permits LNG ships to enter Boston Harbor only in daylight. The worst meteorological condition that is reasonably applicable during the day is D weather. For D weather the Germeles-Drake model gives a maximum downwind distance of about 3 miles. If the Coast Guard maintains its present rules, we believe that for spills onto water, D weather is the worst applicable stability class and about 3 miles is the maximum downwind travel distance.

The other areas of comment pertain to:

- The sensitivity of the Germeles-Drake model to chosen values of the entrainment constant α.

- Comments on the Fay-Lewis model.
- Comparison of Fay-Lewis and Germeles-Drake models.
- Recommendations for further work on the SAI model.
- Further comments on the choice of applicable weather stability classes.

These subjects are considered in more detailed below.

Entrainment Constant Sensitivity. - On page 54 and in Figure VI-5, Dr. Havens presents the results of parametric studies in which he varied the entrainment constant α over the range from 0.01 to 0.5 in the Germeles-Drake model. The resulting large sensitivity led him to conclude on page 117 that there is too much uncertainty in the Germeles-Drake model. It is not reasonable to consider values of α as large as 0.5. There is no known nonenergetic entraining system that entrains such large amounts. As pointed out in Reference 4, a reasonable value for α is 0.1; a value as large as 0.15 might be possible, but surely nothing larger than about 0.2. The conclusion that there is too much uncertainty in the Germeles-Drake model is therefore not warranted. As can be seen from Figure VI-5, for reasonable values of α (about 0.1), the uncertainty in the values predicted by the Germeles-Drake model is relatively small.

Comments for Fay-Lewis Model. - Two important parameters in the atmospheric dispersion phase of the model are the radius (r_e) and the height (h_e) of the cloud at neutral buoyancy.

For a spill of 25,000 m^3, Dr. Havens has used the values given by the Lewis thesis : $r_e = 816$ m and $h_e = 2.9$ m. Fay and Lewis claim that these dimensions are the dimensions of the cloud at neutral buoyancy. Simple arithmetic will show that a pure methane cloud of mass equivalent to that from a 25,000 m^3 LNG spill must be at -259°F in order to have these dimensions -- and therefore the cloud is not neutrally buoyant. Apparently, there is a basic physical inconsistency in the Fay-Lewis model. This raises very serious doubts about the values used for r_e and h_e and about the credibility of the entire analysis.

Another fundamental question on the Fay-Lewis model involves the true asymptotic behavior of Equation (VI-5), which has been proposed by Fay and Lewis for calculating LNG vapor dispersion in the atmosphere. Fay and Lewis have claimed that, under certain conditions, this equation is asymptotic to Pasquill dispersion equations (namely, Equations (VI-3) and (VI-4)), thus leaving, perhaps, the impression that Equation (VI-5) is not that different from classical Pasquill dispersion. However, the required conditions are not met by the LNG vapor dispersion cases considered in this work. This point is illustrated by the following table, which was derived for the spill size considered (25,000 m^3 with $r_e = 816$ m and $h_e = 2.9$ m):

Downwind Distance (Km)	Stability	σ_{yI} (m)	σ_{zI} (m)	Methane Concentration from Eq. VI-3	VI-4	VI-5
27	Very Stable	176	25.2	0.99	0.092	0.050
51	Very Stable	310	37.2	0.22	0.062	0.025
2.3	Neutral	74.3	33.8	4.13	0.068	0.050
4.8	Neutral	146	56.6	0.64	0.041	0.025

Fay and Lewis state that Equation (VI-5) is asymptotic to Equation (VI-3) for $\sigma_{yI} \gg r_e$ and $\sigma_{ZI} \gg h_e$ (large distances), and to Equation (VI-4) for $\sigma_{yI} \ll r_e$ and $\sigma_{ZI} \gg h_e$ (intermediate distances). The above table shows that these conditions are not met. The results from the various equations differ considerably. The only place where the asymptotic criteria seem to be met is in the third line, but even here the results from Equations (VI-4) and (VI-5) differ by 36% because, evidently, the criteria for intermediate distances are not satisfied in the required sense. Contrary to the claims of Fay and Lewis, Equation (VI-5) is not close to Pasquill dispersion for LNG-cloud dispersion calculations of practical interest.

Dr. Havens has also shown the large difference between Equation (VI-5) and classical Pasquill dispersion equations (see Figure VI-1), but does not point out the implication stated above, that the Fay-Lewis dispersion model is not of the Pasquill type. Instead, Dr. Havens states repeatedly that dispersion in the Fay-Lewis model is based on Pasquill dispersion (see pages 26, 35, 40 and 46). Still another question that might be raised is: If, indeed, dispersion in the Fay-Lewis model is not of Pasquill type, then are dispersion coefficients, formulated and quantified for Pasquill dispersion, applicable to non-Pasquill dispersion techniques? (The Slade coefficients used by Fay and Lewis are Pasquill dispersion coefficients.)

Comparison of Fay-Lewis and Germeles-Drake Models. - On page 56, Dr. Havens states that predictions of downwind vapor travel from the Fay-Lewis and Germeles-Drake models "during neutral and stable atmospheric conditions are in close agreement". According to Tables VI-3 and VI-4, predictions from the two models differ by about 40% to over 60% under all conditions analyzed. This is not close agreement. Further, in view of the several inconsistencies in the Fay-Lewis approach, any agreement between the two models is fortuitous.

Recommendations on SAI Model. - The SAI approach to calculating downwind travel distances has a number of attractive features from a theoretical point of view. We, however, have not been able to either check their estimates or to ascertain the relative importance of the differences between the SAI model and the Germeles-Drake approach. We recommend that efforts be made to make a more direct comparison than Dr. Havens has made and that the SAI model be tested for its sensitivity to important parameters. It would be of great interest to us if the SAI model confirmed that our estimate of about 3 miles for maximum downwind distance is, in fact, conservative.

Applicable Weather Stabilities. - For his comparisons, Dr. Havens uses stability classes D (neutral) and F (most stable) with the Germeles-Drake model and computes maximum downwind travel distances of about 3 and 10 miles, respectively, for 5% average concentrations. Dr. Havens states on page 13 that he used "the "worst applicable" meteorological conditions suggested by the groups". Lest the impression is left that

flammable concentrations might travel downwind to 10 miles and more, we must emphasize that we consider calculations based on class F weather as academic and of little practical significance. In our opinion, the "worst applicable" class is D and, therefore, about 3 miles is an upper bound for the downwind travel of 5% average concentrations. Our reasons for considering class F (and even class E) as inapplicable are as follows:

(i) According to Turner (Reference 27, page 6) classes E and F are possible only during nighttime.

(ii) Current Coast Guard regulations require that LNG tankers come into port only during daytime.

(iii) According to Turner (Ibid), the standard Gifford Pasquill classes have been defined for "open country or rural areas". It is important to keep in mind that in calculating LNG vapor dispersion as a part of safety analyses for metropolitan areas, more unstable classes should be used because of "the larger surface roughness and heat island effects" of such areas.

From a practical point of view, Cabot does not regard large vapor cloud travel distances as a reasonable possibility. The conditions specified by Dr. Havens on page 15 of the draft are extremely unlikely, if not impossible, if one takes into account the strict Coast Guard rules that have been applied in Boston Harbor. Massive spills from LNG tankers

would require a highly energetic collision with a large ship and we believe that this possibility is eliminated by Coast Guard rules creating a traffic-free harbor. Under these circumstances, the estimation of vapor travel distances is an interesting mathematical exercise done in response to the National Environmental Policy Act.

The results of these vapor travel calculations, however, need to be placed in the proper perspective as one element of a careful risk analysis. Risk is a function of both the probability and the consequences of an undesired event. The relevant probability includes early ignition as part of an event leading to a large spill as well as the likelihood of ignition by land-based and water-based sources. And the resulting risks can only be assessed on a realistic basis if the fire hazards are compared with other flammable, although less volatile, fuel substitutes for LNG.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF MECHANICAL ENGINEERING
CAMBRIDGE, MASSACHUSETTS 02139

JAMES A FAY
PROFESSOR

March 10, 1977

Dr. Jerry Havens
Office of Merchant Marine Safety
U.S. Coast Guard
400 7th St., S.W.
Washington, D.C.

Dear Dr. Havens:

Enclosed are my comments on your draft report. At the very end are two detailed comments which you may wish to delete if you make corrections to the necessary parts of the draft paper.

Thanks for the courtesy of asking for my comments.

Sincerely yours,

J A Fay

James A. Fay

JAF:daf
cc: H. Walter
enc.

COMMENTS ON "PREDICTABILITY OF LNG VAPOR DISPERSION FROM CATASTROPHIC SPILLS ONTO WATER: AN ASSESSMENT"

James A. Fay

Massachusetts Institute of Technology

This excellent review serves two very important purposes. It compares the predictions of the several LNG vapor cloud dispersion theories on a common basis, i.e., a given spill size and distances to given ground level concentrations. More importantly, it explains in full detail the various assumptions and calculation procedures used in each theory which are not always adequately described in the original publications. The disparate predictions of the various approaches are well illustrated and some of the intermediate steps in determining the downwind concentrations are usefully contrasted. It will be very helpful in clarifying the state of knowledge regarding vapor cloud dispersion and suggesting further analytical and experimental approaches to a more reliable method of prediction.

The discussion in the introduction (pp. 15-17) of the probability of various accident scenarios, which is clearly not an aspect of the scientific review of the various dispersion theories but more nearly a policy statement regarding risk, unfortunately tends to denigrate the value of this analysis. The reader may wonder whether the assessment is to be taken seriously, or has been carefully made, given the asserted unlikelyhood of the process being discussed. But if one ignores the casuistry of this portion of the introduction, the subsequent analysis is scientifically useful and more than worth the effort to have performed it.

On p. 35 (and inferentially in Table VI-2) it is stated that the instantaneous spill models assume that the vapor cloud radius and the liquid pool radius are equal at the end of the evaporation period. Neither Fay (24) nor Fay and Lewis (6) make this assumption, nor is it necessary for the determination of vapor cloud spread according to their analysis, but this assumption is used by Germeles and Drake (4) (see Fig. VI-3) and the FPC staff (7) (see p. 80) as an intermediate step in determining vapor cloud spread. I expect that the vapor cloud will extend beyond the edge of the pool at the end of the evaporation period, but this point obviously deserves further investigation.

In determining the molar concentration of LNG according to the method of Fay and Lewis (6), the instantaneous source strength Q in Eq. (VI-2) and the equation following it should be the volume of pure vapor at atmospheric temperature, i.e., 590 times the liquid volume or 2.45 times the saturated vapor volume at atmospheric pressure when the air temperature is 0°C. Since the Gaussian puff vapor dispersion equations conserve the partial volume of the dispersing material and hence assume a constant temperature dispersal process for the gas contaminant being dispersed, the equivalent source strength should be the constant partial volume of vapor at atmospheric temperature. Thus the initial vapor cloud height h_v in Eq. (VI-3) and subsequent equations should be determined from this instantaneous source strength according to $h_v = Q/\pi r_{vm}^2$.

For the purpose of determining the maximum radius r_{vm} of the vapor cloud at the point of neutral buoyancy, Fay (24) assumed that the vapor cloud motion would be the same as that of an adiabatic cloud of saturated vapor equivalent to the spill volume and spreading for a time needed

to transfer heat sufficient to render it neutrally buoyant. The height of this adiabatic cloud at the end of the cloud spread period should not be used as the starting point for the dispersion calculation for the reasons given above.

The comparison shown in Fig. VI-1 is very useful in that it shows that the Fay and Lewis (6) dispersion model cannot be adequately represented by a point source model even at the largest distances of interest. This is a consequence of the effect of gravity spread of the vapor cloud in the early stages which produces an initial shape quite different from that which eventually ensues far downstream. It is also apparent from a close examination of this figure that a "virtual source" solution of the form of Eq. (VI-9) will also fail to match the Fay and Lewis solution over most of the region of interest, for the same reason.

The inability of virtual source models to account for the initial cloud shape is well illustrated by the Germeles and Drake (4) solution for neutral stability (p. 52,54). At the actual source, where the gravity spread model concentration is matched to the virtual source puff model concentration, the gravity cloud radius is 750 m and the height is 18.4 m (Fig. VI-3). In contrast, the virtual source model horizontal and vertical deviations at this same point can be found from Appendix I to be 280 m and 82 m respectively. Thus the puff model aspect ratio (width/height) is nearly one twelfth that of the calculated cloud at the point where the former is supposed to depict the beginning of the dispersion process. It would seem that the virtual source models are inappropriate for describing dispersion of clouds of such unusual shape.

The difficulties inherent in a virtual source model are also illustrated by the CHRIS model (p. 77). The concentration calculated from Eq. (VIII-15) evaluated at the actual source, for the case of F stability (for which 5% concentration is reached at 86,000 m) is 2226%! Thus this model predicts concentrations exceeding 100% for very long distances from the spill.

In addition, the use in CHRIS of a steady source model for a source of finite lifetime leads to quite peculiar results. Since streamwise diffusivity does not enter the calculation, the streamwise cloud dimension would approximately equal the wind speed times the evaporation time or about 500 m. But for F stability, the plume transverse and vertical deviations at 5% concentration are 19000 m and 90 m respectively. Such an odd-shaped cloud, with the transverse dimension 40 times the streamwise dimension, does not seem consonant with known dispersion characteristics.

The calculation according to the Germeles-Drake model of the effect of different entrainment rates on vapor concentration during the gravity spreading phase of the vapor cloud motion, as depicted in Fig. VI-5, clearly indicates the significance of assumptions regarding the magnitude of this process, as the author emphasizes on p. 117. These assumptions are equally important to the SAI model. In my opinion, the very rapid dilution calculated by SAI is directly related to their assumed (and presumably high) values of vertical momentum diffusivity.

Entrainment coefficients rarely exceed 0.1, and then only for mixing processes across gravitationally unstable interfaces. Indeed, the observation that intrusions exist for layers having very large values for the ratio of horizontal to vertical dimensions indicates that

entrainment coefficients must be very small for gravitationally induced motion of this type. While the parametric study of the effect of various entrainment coefficients on gravitational spread is a useful analytical tool, it is doubtful that the calculations for high entrainment coefficients are describing physically realizable processes.

The vertical momentum diffusivity used in the SAI model appears to affect the results significantly since it determines the entrainment rate during gravitational spread. The explanation given on p. 108 of the choice of stability parameter (which affects the choice of diffusivity) is not sufficient to enable a reader to reproduce the SAI prescription. A more precise explanation is very desirable.

Important information for the FPC model appears to be lacking. The heat transfer coefficient h used in Eq. (VII-25) is not specified nor is it explained how it is to be determined. Similarly, the origin of the heat transfer coefficient used in Eq. (VII-28) should also be explained. It would also be important to obtain from the FPC staff a physical explanation of the vapor release process calculated on p. 84 if any serious consideration is to be given to this model.

It would be more accurate to describe the dispersion models (p. 113) as including the effects of gravitational spread as a precursor to neutral buoyancy dispersion or as the determinant of the initial conditions for the latter. The model may or may not include entrainment during the spreading process, but if it does the mixing is related to spreading speeds and not to atmospheric turbulence. These models also conserve mass, momentum and energy (to various approximations) as does the differential equation (SAI) approach.

The author's suggestion that heat and momentum transfer effects on the vapor dispersion from small scale spills is unimportant (p. 114-116) may be true, but the evidence in support of it given by the author is far from convincing. First of all, it is a confined land spill (in contrast to the water spills exclusively treated in this paper) which is considered. Secondly, given the kind of disagreement between the models for a large water spill, all of which (including Burgess' model) include gravity effects to a greater or lesser degree, the comparison in Fig. IX-1 is probably fortuitous. But certainly this is a matter deserving further thought and analysis.

The advantages of the differential equation model, such as SAI model, are not so one-sided as the author suggests on p. 120. For example, such models will not predict the observed dispersion in homogeneous turbulent flow. But since the vapor cloud is being dispersed in the atmospheric shear layer, the approach of relating the local diffusivity to the distance from the surface and the local gravitational stability parameter may be a reasonable approximation. Nevertheless, it would be very desirable to compare such solutions with measurements of dispersion of passive trace diluents. Also, there are other practical disadvantages to such models, for example, expense of obtaining solutions and hence testing for the sensitivity to various assumptions.

In summary, these comments are made to elaborate and develop several of the points raised by the author and thus to improve the general level of understanding of this difficult problem.

DETAILED COMMENTS

On p. 41, the argument of the exponential term in Eq. (IV-2) should read $(-z^2/2\sigma_z^2)$. This follows from Eq. (1) of Fay and Lewis (6) for the case of $r = 0$.

For the reasons explained above, regarding the determination of h_v, the height in item II, Tables VI-3 and VI-4 should read 7.1 m under column one. The corresponding distances in items IV and V of column 1 should be 28.0 miles and 47.2 miles in Table VI-3 and 3.0 miles and 5.3 miles in Table VI-4. Line 5 in Table IV-1 should thus read 28.0 miles. Also, Fig. VI-1 should be modified accordingly.

FEDERAL POWER COMMISSION
WASHINGTON, D.C. 20426

March 3, 1977

Mr. Jerry A. Havens
Cargo & Hazardous Materials Div.
U. S. Coast Guard (G-MHM/83)
Washington, D. C. 20590

Dear Sir:

I appreciate the opportunity to review and comment on your draft report "Predictability of LNG Dispersion from Catastrophic Spills into Water -- An Assessment." It is useful to have a review of these dispersion models under one cover, and you have done a good job of placing them in perspective. I agree completely that "The SAI model . . . is a significant advance . . ." (page 119). I would hope that in the future no U. S. Government agency would support any more work or spend any more staff effort on development of any LNG dispersion model less adequate or complete than this.

In general, the report appears to be heavy on providing everyone's equations, but light on why the models are inadequate ("assessment" is in the title). Thus, given the evident quality of the SAI model and its reasonable limits for downwind vapor travel, I would suggest a concise summary of reasons why those models that produce much longer plumes -- by factors of 10 to 40 times too much (page 14 and page 34) -- are so erroneous. Such a summary of how each model is deficient compared to SAI would be helpful, particularly in FPC cases involving LNG applications. These models have caused considerable confusion and delay in hearings. Having such material available before hand could markedly shorten the hearing process.

It is most unfortunate that you have placed so much emphasis on LNG spills of 25,000 m^3, which is a size that is probably too large ever to be observed. The following calculation illustrates this point.

Mr. Jerry A. Havens

The probability of a water spill from an LNG ship accident is the product of the probability of an accident times the probability of a spill given an accident. A way of estimating the accident probability is to consider LNG tanker operating experience. I have estimated recently that since 1964 there have been about 1,600 LNG tanker voyages worldwide, or 3,200 tanker transits of ports, harbors, or piers while loaded with cargo, without a major accident or major spill. From this observed excellent accident rate an estimate of the true accident rate may be made using standard statistical techniques. The result is about:

$$1.5 \times 10^{-3} \text{ accidents/transit}$$

for all types of accidents.

In order to get a feeling of the probability of a 25,000 m^3 spill from a tanker accident consider that this is equivalent to about 6.6×10^6 gallons of oil in volume. The probability of such an oil spill in U. S. ports, harbors, or piers, based on data from the Oceanographic Institute of Washington, 1974, is about

$$e^{\frac{-25,000}{1,570}} = e^{-16} \simeq 1.1 \times 10^{-7} \text{ spills per accident}$$

This is discussed more fully in the FPC Final Environmental Impact Statement on Alaska Natural Gas Transportation Systems, April 1976, Vol. III, page 410-413. This important reference does not seem to have been included in your list. Thus the probability of such a large spill is about 1.7×10^{-10} per transit, which is indeed negligible for any foreseeable annual rate of LNG deliveries worldwide.

This view is underscored by the FPC Administrative Law Judge in his "Initial Decision on Proposed Alaska Natural Gas Transportation Systems," FPC, February 1977, in which he states in part: (page 94) "The fear raised by those opposing LNG facilities in populated areas requires, therefore, certain assumptions. First, there must be a large spill." (Page 95) "In order to achieve the large size vapor cloud necessary to create even measurable risks for people located some distances away, an assumption has to be made that a high volume of LNG be released instantaneously . . ." (page 95) "LNG is hazardous and must be treated with respect. The risks associated with its use must be analyzed. But, they must be done so on a credible basis with assumptions that are in themselves credible, and much of the risk analysis has not been done on that basis." Your otherwise fine report may therefore permit misleading information because it analyzes essentially impossible events.

Mr. Jerry A. Havens

Obviously, plumes from small water spills of LNG ($\leq$100 m^3), while presumably more prevalent, do not represent a public hazard either. The range of interest encompasses spills that are large enough to be a hazard but small enough to possibly occur. Based on probability studies at FPC (in the first reference above), this range is believed to be 500-3,000 m^3. What are the comparative results from the models you have analyzed for this spill-size range?

I note on page 116 that "sufficient accuracy may be obtainable from classical dispersion models for the prediction of LNG vapor dispersion from small spills on land or water," where "small" is not otherwise defined. It would be helpful to know the accuracy expected from these models compared to the SAI model in the above spill-size range. The loss in accuracy may be more than offset by the substantially lower cost incurred from their use. Likewise, it would appear to be worthwhile to perform sensitivity analyses on the SAI model in this spill-size range in order to reduce it's computation cost without sacrificing significant accuracy. Such sensitivity analyses should be supported.

The discussion and rationale on page 15 for performing this assessment of downwind vapor plumes, in spite of the probability of prompt ignition of the LNG vapor being "extremely likely," seems shaky. The truth is that the available accident reports from the Coast Guard show that the probability of prompt ignition after oil tanker accidents is not known accurately, but appears to be reasonably large -- perhaps as large as 90 percent. Many witnesses at FPC hearings, including the writer, believe that this is probably true for LNG tanker collisions also (but here again there are no data). Extrapolating to LNG tankers, a 10 percent chance of non-ignition with a subsequent hazardous plume is sufficient cause for your assessment, I should think, without confusing the reader further. In short, I do not equate "highly unlikely" with a 10 percent probability.

Let me compliment you on a thorough, clear, and timely report. It is most important that someone from outside the LNG community perform such an assessment at this time.

Sincerely,

Theodore S. Needels

Theodore S. Needels
Environmental Specialist

February 16, 1977

Dr. Jerry Havens
Technical Advisor
Hazardous Materials Division
United States Coast Guard
Washington, D.C. 20590

Dear Jerry,

I want to thank you for the extra effort it took in seeing that I got a copy of your draft report on the "Predictability of LNG Vapor Dispersion". We still don't know what happened to the first copy that was sent.

I want to compliment you on the very excellent report which you have prepared. I certainly feel it was an extremely worthwhile effort for someone who was not directly involved in the LNG community to evaluate the various models which have been used to produce the wide range of answers often quoted or misquoted by non-technical individuals.

We have a very limited number of comments which you might consider incorporating into your report. They are as follows:

Page 13

In the final line of the first full paragraph, you note properly that the worst applicable meteorological condition suggested by the groups is not necessarily the worst that might have been assumed. I wonder if it might not be worthwhile siting the fact that the SAI result quoted, for example, is far from its own predicted worst case associated with a high wind condition.

Page 15

In the sixth and seventh lines of the first paragraph, the point is made that ignition will probably occur in a high energy collision because of frictional heating anticipated. While we agree that this could play a role, it is our personal feeling that sparks and/or broken electrical lines or connections would produce an even more reliable ignition source than that associated with frictional heating.

Page 21

The first accumulation term should contain a ρ, i.e., $\frac{\partial \rho H}{\partial t}$.

Page 95

Under the section entitled "Accountability of Momentum", the statement is made that equation VIII-2 is expanded with vertical accelerations and viscous forces neglected in the equation for accountability of vertical momentum. Another view of this would be to say that the vertical accelerations and the viscous forces are assumed equal and opposite. This results in the same equation VIII-5c, but does not give the sometimes mistaken impression that vertical velocities are set equal to 0, which in fact, as you realize from the other equations, are not.

Pages 102-103

There is a spurious ρ in the horizontal diffusion terms of the conservation equations for $\bar{u}$, $\bar{v}$, $\bar{H}$, $\bar{c}$, i.e.

$\frac{\partial}{\partial x} K_H \frac{\partial}{\partial x}$ and similarly for the y diffusion terms.

A definition of ϕ should also be provided as $\phi = gz$ (the geopotential height).

Also, the substantive derivative $\frac{D}{Dt}$ takes on a new form in the σ coordinate system as

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + \dot{\sigma}\frac{\partial}{\partial \sigma}$$

On page 103, the ρ equation should contain an RT factor in the denominator.

Page 104

Modifications to this page are shown in the attached copy.

Page 109

The final sentence states that the ratios in Table VIII-3 are based on proprietary field data obtained by SAI. This is correct, as stated in any of our reports completed for Western LNG Terminal Company. However, it may also be stated that they were compared with similar data published by Lantz, and the SAI results are conservative, i.e., they would produce smaller diffusivities in the horizontal direction than those using the results of Lantz.

Dr. Jerry Havens
February 17, 1977
Page Three

Page 111

In the third line of the first full paragraph, it is stated that SAI has not published their calculated results for a 25,000 m^3 spill. I think it is more properly stated that SAI has not calculated the dispersion associated with a 25,000 m^3 instantaneous spill.

For your additional information, I have enclosed a response, which we prepared for Western LNG Terminal Company, to a question from the FPC regarding more detailed information on the numerical methods used in the SIGMET code. I trust it will be of some value to you.

Again, let me congratulate you on a very excellent report.

Sincerely,

SCIENCE APPLICATIONS, INC.

Walt

Walter G. England
Manager
Environmental Sciences and
Safety Division

WGE:li
encl

Arthur D. Little, Inc. ACORN PARK · CAMBRIDGE, MA 02140 · (617) 864-5770 · TELEX 921436

March 4, 1977

Dr. Jerry Havens
Technical Advisor
Cargo and Hazardous Materials Division
Office of Merchant Marine Safety
United States Coast Guard
Washington, DC 20590

Dear Dr. Havens:

Thank you for the opportunity to review your comprehensive assessment of the various models in use for prediction of vapor dispersion from potential LNG spills on water. Unfortunately, I did not have time to make a detailed review of the report, so my comments are primarily based on impressions from a once-through reading of the report and on my own concerns about the strengths and weaknesses of the various models.

My colleague, Dr. Germeles of Cabot Corporation, has discussed with me and sent me a copy of the comments he is sending you based on his quite thorough review of your analysis of our model and the Fay-Lewis model. I concur with essentially all of his remarks.

My chief concern is that the draft report may give the impression to a reader who is not thoroughly versed in the technical issues that you are recommending the SAI model as the best available. While I concur that their approach is the most rigorous, I strongly share the concerns you express later in your report that the SAI model needs much additional checking, sensitivity testing and verification before it should become a recommended method. The model developed by Dr. Germeles and myself is simplified to the point of including physically unrealistic assumptions; however, these assumptions can be defended as being conservative. While we would expect our model to overpredict downwind hazard distances, I doubt that one could sort through the many assumptions incorporated in the SAI model and say whether the net effect is conservative or optimistic. (This gets back to your concerns about the sensitivity of the model to key parametric assumptions.)

My major concerns with the SAI model are in the following areas:

1. Since the SAI model is proprietary and very expensive to execute, it has not yet been extensively studied by an independent expert like yourself.

2. The SAI model should be as sensitive to choice of mixing parameters as the GD model since the same basic phenomena are involved.

3. The SAI model check with "data" are not a real verification since the small land spill test used in the comparison was not large enough to have discernible gravity spreading behavior. In fact, a simple line source Gaussian model also is in good agreement with the data.

4. Any large computer programs are difficult to verify since they may contain insidious errors or be subject to subtle numerical instabilities. Only by extensive sensitivity testing, comparison with analytical solutions for simple test cases, comparison with any pertinent experimental data available (e.g. gravity spreading from small spills under calm wind conditions), and careful selection of values (and uncertainty bands) for important parameters can one gradually build confidence in a complex computer model.

5. The turbulent mixing parameters used by SAI are based on their own data. When these are compared with the widely used Pasquill-Gifford coefficients, it appears that the SAI parameters themselves may partially be responsible for minimizing the effects of atmospheric stability on downwind travel.

6. The increasing downwind travel distances with increasing wind speed are physically possible but have never been observed in practice. Whether or not this is real could probably be shown only by a series of extremely large (and costly) experiments.

Given these uncertainties, I would have preferred you to emphasize that 1) the G-D model gives simplified, but conservative estimates of downwind travel and 2) that the SAI approach is an attempt to obtain a more physically realistic answer but that the model itself still requires further testing and scrutiny before it can be recommended per se.

The ironic part is that all these models are being developed for use in risk assessment studies or for definition of some maximum accident scenario. In fact, the present ranges of uncertainties in the models are not large compared to uncertainties in defining spill scenarios (quantity and

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rate) or in the distributions of population and ignition sources in the path of a hypothetical vapor cloud. In the SAI risk assessment, it is their conservative estimate of ignition source distribution -- not their vapor cloud analyses -- that determine the potential hazards. With uncertainties such as these in other assumptions about accident scenarios, perfection of LNG vapor dispersion models seems to me to be more of a technically interesting goal than an urgently needed effort. (Even then, for risk studies, cloud width is a much more important parameter than maximum downwind travel.)

I'm enclosing a few quick calculations using the CHRIS model for an instantaneous 25,000 M^3 spill which are slightly different from those in your report.

Please phone me if you'd like to discuss any of these points further. Your report is an excellent contribution and will be widely disseminated, so I'm sure we all would like to see it as fair and easily understandable as possible.

With best regards.

Sincerely,

Ly Drake

Elisabeth M. Drake

EMD:km

cc: Dr. A. Germeles/Cabot Corporation
D. S. Allan/Arthur D. Little, Inc.